

ELEMENTS OF
TROPICAL SOIL SCIENCE

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ELEMENTS OF TROPICAL SOIL SCIENCE

BY

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SECOND EDITION

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TO MY FAMILY IN THREE GENERATIONS

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PREFACE

DURING nearly twenty years spent in advising tea planters on their practical problems, I have often been asked to recommend a suitable text-book on soils, manures and agricultural chemistry in general. Of the many books, excellent in themselves, that have been current during this period, none, so it seemed to me, was an obvious choice. Most of them are written from the point of view of temperate zone agriculture, and those which are more general in their treatment are written for students rather than for the practical man. On the other hand, books on tropical agriculture devote little space to the soil, its properties and cultivation, and their material is for the most part out of date.

This book is a small contribution towards filling the gap. I have made my objective a limited one and have restricted myself to those aspects of the subject which most frequently arise in advisory work : to be useful, a book must be short. In dealing with theory, I have tried to give just sufficient to act as a framework to support the practical applications, and I have reduced tables and diagrams to a bare minimum.

The material on which these chapters are based, has been drawn from a variety of sources too numerous to acknowledge in detail. I owe a particular debt to the Rothamsted Experimental Station where I first came into contact with agricultural research and with the practical farmer. The numerous members of the planting com-

munity, with whom I have discussed problems in the course of my advisory duties, have been my teachers in a very special sense.

I am greatly indebted to Professor J. A. Prescott, Dr. T. J. Marshall and Dr. C. S. Piper, of the Waite Agricultural Research Institute, Adelaide, South Australia, and to Mr. E. A. Cornish, for valuable criticisms of the manuscript during preparation. Their help removed a number of blemishes: those that remain must be held to my account.

I am glad to acknowledge the permission of the Director and Board of the Tea Research Institute of Ceylon to make use of data compiled in the laboratories of the Institute. For permission to reproduce data published in *Endeavour* (Fig. 1) and the *Empire Journal of Experimental Agriculture* (Fig. 5) my thanks are due to the Editors and to Imperial Chemical Industries Ltd. and the Clarendon Press respectively.

Finally, I wish to thank my brother, Mr. W. A. Eden, for undertaking to see the manuscript through the press.

St. Coombs,
Talawakelle,
Ceylon.

T. EDEN

December, 1945.

PREFACE TO THE SECOND EDITION

THE advances made since 1947 in many fields of research bearing upon the principles of tropical soil science have made necessary a revision of the text of even so elementary an exposition of the subject as is contained in this book. In the meantime also I have extended my working knowledge of tropical soils to the African continent and have thus seen many problems in a new perspective.

Accordingly I have modified and extended several sections of the book and added two new chapters. The additions to existing chapters relate chiefly to the genesis of laterite and catenary systems; the water relations of soil; the principle of base exchange in soils as influencing salinity and alkalinity of soils under faulty irrigation practices, and the remedial measures required. Changing trends in fertilisers have also been noted.

The incidental references to the problem of the availability of nutrients have been removed from Chapter III and reconstructed with new material into a separate chapter. In addition, in order to put into perspective the various methods of soil amelioration and conservation described in Chapters VI to VIII I have attempted in Chapter IX a brief review of the long term problem of fertility maintenance.

During the preparation of this edition I have had no official institutional connection. I have had however the good fortune to live in the vicinity of the Rothamsted Experimental Station and the Commonwealth Bureau of

Soil Science, and to enjoy the incomparable resources available there. It is a special pleasure to acknowledge again my continued debt to Rothamsted during my forty years of professional work. I am particularly grateful to Mr. D. H. Boalch for library facilities; to the late Dr. H. Greene for sending me his valuable circular letters on recent advances in soil research in the tropics, and to Mrs. M. K. Milne for help in locating literature.

Dr. E. M. Chenery, Director of the Tea Research Institute of East Africa was kind enough to make a number of suggestions about revision from which I have been able to benefit.

To Dr. H. L. Penman, O.B.E., F.R.S. and the Editor of "Weather" I am indebted for permission to reproduce Figure 1. and to the Editor of "Outlook on Agriculture" and Imperial Chemical Industries Ltd., for similar permission in regard to Figure 6.

T.E.

Sidmouth.

May, 1964.

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CHAPTER I

SOIL : ITS ORIGIN AND FORMATION

THE exposed surface of a quarry, railway- or road-cutting shows that soil in the agricultural sense is a very thin skin on the earth's surface. Often at no great depth the more or less loose material ends abruptly on solid rock. In favourable instances, where natural agencies have not exerted a mixing effect on the soil layer, it is possible to trace the transition from rock to soil in well-defined stages starting from unchanged rock in the lower reaches, and finishing with a surface layer which appears to bear little relationship in colour and texture to the bed-rock below. Overlying the solid rock there may be a layer of rock fragments separated by intrusions of material that is little more than soft rock. In this the details of structure of the mother rock will still be visible, particularly if the rock is crystalline and not very homogeneous in character. The nearer to the surface the examination is made, the greater the changes that are encountered till, at the surface, there is a layer which is recognisable as soil in the agricultural sense.

Soil Formation : Processes of Disintegration and Integration

This picture of soil formation from the solid rock by recognisable gradations is typical of some soils only : those in fact that have been formed in the place where we now see them. Many soils have been formed in one place and

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have been moved by past geological agencies, such as ice movement, and by past and present erosion, to localities far from their place of origin. But in general, there is no difficulty in recognising the fact that the process of soil formation is in the first place a process of rock disintegration.

More detailed examination, such as can be carried out with a microscope and by means of chemical analysis, shows that the alteration proceeds much further, and involves not merely a progressive fragmentation of rock particles but includes changes in their chemical constitution also. When the chemical nature of the soil changes, its physical nature alters as well, so that in the final phase the soil is quite different in properties from the rock from which it has been derived.

If disintegration were the only process occurring at the exposed surface of rock, the result would not be soil in the agricultural sense of the word. Soil as a medium for the cultivation of crops, or for the maintenance of natural vegetation, is quite different from crushed rock, with or without the more fundamental changes in the chemical constitution of the original material. In the uppermost layers there are building-up processes at work which are associated with the activities of living organisms and their dead remains. Until these activities reach a certain level of intensity and exert their peculiar influence on the purely mineral material derived from the rock, influences bearing both on composition and structure, soil as an agricultural entity cannot be regarded as having been formed.

The disintegrating forces at work on exposed rock are primarily climatic, and their combined effect is spoken of

as "weathering". Water is of prime importance. Its solvent effect though prodigiously slow is extensive, and to this must be added the mechanical disintegration caused by the jostling of one particle against others when running water attains enough force to bear with its solid particles. Expansion and contraction due to variable temperatures produce stresses and strains in the larger fragments which lead to tiny fissures that other agencies can enlarge. In temperate and sub-temperate climates the expansion of water at the moment of ice formation (whereby the volume occupied increases roughly by eleven per cent) exerts great pressure and plays an important part in the weathering process. In some parts of the world, wind has played a conspicuous part in soil formation and deposition.

Coupled with the more striking forms of weathering is the slower process of oxidation brought about by the oxygen of the air. Reinforced in parts of the world by high temperatures, which speed up chemical action, contact with air brings about a gradual breakdown of the varied complex materials present. New compounds are formed with new properties of combination and solution, of hardness and softness; all of which have a cumulative effect. Although its inclusion anticipates a later section, carbon dioxide must be added to the list of weathering agents. Dissolved in water it is a weak acid, and for most of the mineral constituents its solvent action is very much greater than that of simple water.

The integrating activities occurring in soil are largely the work of living organisms, both vegetable and animal. The higher plants, that is those provided with the green pigment chlorophyll in their leaves, have the capacity of

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extracting carbon dioxide from the air and of building it up with hydrogen and oxygen from water, and with soluble nitrogen absorbed with that water, into complex chemical substances.

Lower forms of plant life, the bacteria and fungi, abound in the surface soil, and have not the power to use carbon dioxide directly. They live on the dead remains of the higher plants. As they live, they breathe; and it is their respiration that provides the carbon dioxide in the soil air which helps the weathering process.

The decay of the higher plants, and of the micro-organisms and zoological life that feed on them leaves behind a characteristic residual material *humus*. It is the presence of this material along with the purely mineral particles that makes an agricultural soil. Such soil contains a variety of mineral elements and also carbon, hydrogen, oxygen and nitrogen derived from dead organisms in various stages of decay. We have still to account for the nitrogen, an element not usually present in the mineral combinations. Some bacteria living freely in the soil are able to absorb and use nitrogen gas from the soil air. To their activity and adaptation in past geological ages we owe the primary inclusion of nitrogenous materials in soil. There are also other bacteria that have become specifically associated with the leguminous higher plants, which have a similar capacity. They play an even more important part in maintaining the stocks of nitrogen in soil, and their more detailed consideration will be taken up later, when the interdependence of higher and lower plants is dealt with. For the present it is sufficient to note that some of the most important soil properties depend on the physical

and chemical behaviour of decaying vegetation and its ultimate product humus.

Variety in Soil Formation

In what has been said so far, the picture drawn has been that of a soil formed *in situ* from the solid crust of rock. The molten constituents of the earth's surface cool into a compact mixture of crystals of definite chemical composition. Sometimes this cooling takes place at great depths and under great pressure, as in the case of granite. At other times the process goes on at the surface as with the lavas. Many rocks, however, are not "primary", as these are, but "secondary" in that they have been formed from material already weathered from primary types. Copious erosion has carried these weathered products and deposited them in vast beds, sometimes at the bottom of the sea. The particles become consolidated by pressure or cemented by the dissolved products of weathering, and eventually they are raised by geological earth movement and become secondary rocks. Such sedimentary rocks include the sandstones, the quartzites, the limestones, and chalks, these latter being originally derived from the skeletal remains of living organisms from which they derive their carbon. Slate is an example of a fine sediment that has been consolidated by earth pressure.

From these secondary rocks a subsequent weathering forms still further varieties of soil, and in the case of alluvial deposits a soil is formed which has no immediate connection with the rock, either primary or secondary over which it lies. Heat, pressure, erosion, cementation, glacial action, volcanic extrusions all combine to modify

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and mix the types of rocks which cover the earth's surface, and to vary their physical and chemical constitution and proportions. Amongst the commonest of the one hundred and two elements that go to make up the earth's crust and the atmosphere surrounding it are oxygen, silicon, aluminium, iron, calcium, magnesium, potassium, sodium and phosphorus, but there are smaller quantities of the other chemical elements which sometimes play an important part in fertility. Copper, zinc, manganese, boron, molybdenum, chlorine and sulphur, some in minute traces, contribute to the chemical make-up of rocks and of the soils derived from them.

At first glance it might be thought that considering the variety of conditions and rocks which contribute to soil formation, there would be an equally great variety of soil types, but this is true only to a limited degree. Soils are only the residue left from the parent material after a long and drastic process of weathering. In the course of this weathering some constituents are more easily changed and removed than others. All chemical reactions are greatly influenced by the concentrations of the reacting materials and by the temperatures at which they react, and therefore there is ample scope for selective activity in the weathering process. What happens in temperate conditions is quite different from what goes on in tropical regions. Chemical activity in dry zones is vastly different from that in wet regions. Because of these dominating circumstances two tendencies assert themselves. However different the parent materials may originally have been, under any given climatic and weathering conditions, there is a tendency for the end products to be approximately the

same. On the other hand, identical rocks weathered under markedly different circumstances will produce quite different soils. Put in another way, the type of soil found in any locality depends more upon the climatic and weathering conditions than on the parent material in the geological past.

This is a broad generalisation that still admits of a great variety of soil types. Concrete examples of this general principle are best found in those parts of the world such as continental Russia ; in the large land mass of North America ; and in the tropical zones, where vast tracts of land share stable and well defined climatic types. In a climate where rainfall is short ; where the balance of evaporation and rainfall is all in favour of evaporation and where leaching is extremely limited, the resultant soil will have definite characteristics poles apart from that of a tropical soil which is continually leached, and from which the soluble elements are relatively easily and (from an agricultural point of view), irrevocably lost. Anyone familiar with agriculture in both tropical and temperate zones will be equally familiar with a simple illustration of what is being described. A sudden fall of two inches of rain will render soils in the temperate zones unworkable until they have partially dried out. Not a little of the farmer's success in cultural operations depends on his judgment of when to apply his cultivation implements. If he tackles the job when the soil is too wet, it will become puddled and will cake. If he waits till it is too dry, he cannot achieve a fine tilth. With many tropical soils much less skill is needed. Very soon after heavy rain a soil is workable without damage, and a farmer has a much greater

latitude in moisture content at which ploughing and digging can be safely undertaken. Another aspect of this phenomenon will be dealt with under the heading of soil erosion. At the root of this difference lies the type of weathering to which the two types of soil have been subject. In temperate soils alumina and iron are much more rapidly lost than is silica. In tropical soils the reverse is true. Accompanying these differences of chemical constitution are fundamental differences in the properties of the soil particles, some of which will be dealt with in the succeeding chapter.

Soil Horizons and Profiles

It is natural that since air, water and temperature play such an important part in soil formation, their effects should be shown with variable intensity at successive depths from the surface. The surface layers are subject to cycles of wetting and drying quite distinct in character from those at lower levels. One of the most decisive factors in determining what type of soil will be formed is the amount of leaching to which a soil is subject. Soils may be subject to rainfall so heavy and well distributed throughout the year, that soluble constituents and fine particles below the range of even microscopic vision may be continually removed by drainage to lower depths. Or rainfall may be so limited and evaporation so intense that leaching to any depth is impossible so that the soluble products of weathering accumulate in the surface soil. In other circumstances material leached from the upper layers may encounter at lower levels conditions which bring about the deposition of the soluble or suspended

material. These conditions and their innumerable variations exert a profound effect on both the physical and chemical properties of the soil.

When a complete section of a soil mass from surface to solid rock is exposed to view, as in a quarry, it is frequently noticeable that this section or "profile" is divided into distinct layers or "horizons". Instead of there being a slow and imperceptible gradation in colour, texture and organic matter, there are sudden changes from one horizon to another so well marked that the depth of any particular horizon can be easily measured with a rule. These well-defined horizons are the result of the differential effects of leaching from the surface.

During the past fifty years a great deal of attention has been devoted to the study of the whole soil mass from surface down to unchanged rock. The types of horizons that are found have been sorted out and classified, and their chemical and structural properties recorded and defined. The main classification involves three types of horizon as follows :

- " A " horizons from which material is being continually lost by disintegration, solution and drainage.
- " B " horizons which, on balance, are enriched by depositions from A horizons.
- " C " horizons which include the mother rock and such contiguous strata as still show the principal features of the unchanged rock, though the mass may have developed to a crumbling stage.

Each of the types, A and B especially, may have several distinct horizons, so that a soil profile may consist of a sequence that from the surface downward can be labelled

A₁, A₂, B₁, B₂, C. The distinction between A and B horizons, that of being donors or acceptors of material may not be visible by casual inspection. To distinguish between them, and between the intensity of reactions amongst horizons of the same type, recourse is had to chemical and physical tests.

The sequence of horizons showing orderly development and interconnection is often not so simple as that described. Schemes of classification usually arise under circumstances where differences are clear cut. The conception of soil horizons and profiles and their progressive development first arose in Russia. It has been applied with success in America and Australia and in parts of Africa. In tropical zones there is still need for a good deal of clarification.

The branch of soil research we have briefly described is known as pedology (= earth lore). It has played a great part in rationalising soil survey work. Pedology views soil as something to be studied for its own sake, quite apart from its agricultural implications. Because it is a new and actively developing science, its relationship to the agricultural use of the soil has so far made but limited progress. But even at the present stage it has made its impact on agricultural work. It has made soil workers conscious that the agricultural properties of surface soil in which natural vegetation and cultivated crops grow, are intimately related to the properties and development of horizons that are sometimes well below average root range; and has taught them the lesson that they can never confine their attention solely to the very thin layer that is disturbed by the action of cultivation implements.

We have been speaking of the forces that break down

rock and soil particles to smaller and smaller dimensions. The fundamental particles thus produced adhere more or less tenaciously to each other by reason of their changed physical and chemical properties. They form " crumbs " much as the swollen particles of flour do when bread is made and broken. In between these crumbs and their constituent particles are pores which are filled with varying quantities of air and water. It is the type and size of crumbs which to a great extent determine the structure of a soil, with notable effects on its agricultural properties.

Soil Colour

In studying soil profiles the colour as well as the texture of soil distinguishes between the different types of soil and the various horizons in the profile. There is a wide range of colours found in soils of different origin and history. Black, grey, red, brown in all their varying shades and intensities are found in profusion, and occasionally white, yellow and slaty-blue types are encountered. The three most potent factors in determining soil colour are the proportions of silica, iron and humus that they contain. The predominance of brown and red soils is due to the presence of iron and the degree of its oxidation to highly coloured compounds. Leaching and deposition of soluble compounds play a large part in controlling colour changes. Frequently a soil type can be classified directly by reference to its colour changes in successive horizons.

Most of the many soil types recognised by soil surveyors fall into categories according to their colour. In the tropics the red soils are the more prevalent but the black ones are widely distributed especially in low lying

situations. The red highly oxidised soils are formed in conditions of good drainage and correspondingly adequate aeration. Black soils on the other hand are the product of anaerobic conditions where drainage is impeded. Though neither of these soil types can be rated high in fertility, the red soils by reason of their freer drainage are more depleted of bases than the black. cursory consideration would suggest that the black soils are rich in organic matter and the red ones poor. In actual fact colour contrasts are deceptive. Red soils frequently have a higher humic status than a casual inspection would suggest, and black a lower.

The differentiation between red and black soils extends over a wide range of properties both fundamental and agricultural. In a mature soil the particles that largely determine its character are the smallest and most highly weathered; in the terminology of the soil scientist the "clay" fraction. The clay fractions of red and black soils are chemically different. The consequences of this difference will be considered later. For the present it will suffice to say that the typical type of clay in red soils is described as *Kaolinite*, so called from its affinity with Kaolin or china clay. That of the black soils is called *Montmorillonite* from the name of the small French township of Montmorillon some thirty miles east of Poitiers.

Laterite

The red soils are found in great variety. At one extreme are the deep friable loams, changing only gradually in texture and colour, without well-defined horizons, and

easy to cultivate. At the other are massive layers of indurated soil rich in pebbly concretions of iron oxide or blocks of honey-combed material, hardly distinguishable from iron ore, and designated "laterite". Below the surface the type specimen, from the Malabar Coast of India, was soft and could be cut into blocks which hardened on exposure to air to the consistency of a brick. It was used as such, hence the name given to the soil material. (Latin, *latus* = brick.)

In the century and a half that has passed since the name was coined the utmost confusion has prevailed as to what true laterite is, how it was formed, and in what relation it stands to the other red soils with which it is in close proximity.

Chemically laterite is comparatively rich in the oxides of iron and aluminium and low in silica. Two schools of thought about its origin have contended for recognition. The older school regarded laterite as the residue left from the weathered rock when most of the bases and silica had been carried off by the constant leaching action of high tropical rainfall. The modern view is that much more has been happening than a simple removal of material.

Though laterite is now found as a surface layer, often on high ground, the indications are that it was formed at a low level before geological movements thrust it upwards. It is believed to have been formed at some considerable depth, near or at the water-table where the oxygen supply is deficient. The dissolved iron and aluminium carried down by seepage would be in an unoxidised state. As water-tables rose and fell at the alternation of dry and wet seasons the accumulated salts would encounter alternating

conditions of oxidation and reduction, precipitation and solution. The presence of minute particles acting as nuclei for progressive precipitation would encourage the formation of those concretions that are so typical of true laterite. The never ceasing cycles of normal erosion have eventually brought the submerged horizons to the surface, thus exposing the laterite. The pace of erosion has been diminished by the hardening of the exposed material and the laterite cap has accordingly persisted.

This hypothesis does not entirely explain the distribution and variety of laterite deposits but its claims for acceptance are strong. In particular it has clarified one important issue. Low silica and high iron and aluminium content are characteristics that are encountered in other red earths besides laterite. These quite distinct soils have sometimes been described as "lateritic" but this is a misnomer. They have no special affinity with laterite, and they have not been formed at depth. Superficial similarity as regards proportions of silica, iron and aluminium is not sufficient ground for classifying friable and permeable red earths as being generically related to so distinct a soil type as laterite.

Soil Sequences: Catenas

The processes that determine the characteristics of a mature soil are significantly influenced by the topography of the region in which they operate. Laterite is only one example of how water-movement, geological uplift and erosion combine to produce a particular type of soil at a given time in a given situation. In reasonably uniform conditions of parent rock and climate topo-

graphical variations can produce soils of very different character.

In various parts of the world, but very strikingly in East Africa, erosion has carved out valleys from an uplifted continental surface, leaving a series of flat-topped hills of approximately the same altitude alternating with shallow valleys. Across the valley from hill-top to hill-top the soils change in a characteristic manner. The summits have been eroded away to expose rocky outcrops emerging from a shallow stony soil. Lower down the well-drained slope deeper soils occur derived from the weathered remains of rock supplemented by what has been carried down from above by erosion and soil creep. The finer structureless particles of silt and clay are removed to lower depths where they accumulate in the valley bottoms and form impervious and water-logged soils. Across the contours the red or ochre colour of the well-drained soils changes to dark grey or black as anaerobic conditions inhibit oxidation. The soluble bases seeping down from higher levels are immobilized by impeded drainage. Consequently whilst the more elevated soils are in varying degrees acid in reaction the bottom soils are neutral or alkaline and comparatively rich in calcium and other bases. Proceeding up the opposite incline the sequence is repeated in reverse. Milne, the pioneer of East African pedology likened this series to a hanging chain and gave it the corresponding latin name *catena*, each link representing a distinguishable type of soil genetically related to the one above on the one hand, and on the other playing a determinative role in the genesis of a different type lower in the series.

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The recognition of the part played by water movement as influenced by topography has been of considerable value in determining the agricultural use to which land can productively be assigned.

CHAPTER II

THE PHYSICAL PROPERTIES OF SOIL

A SAMPLE of soil taken from the field will contain mineral particles of very different sizes. There may be sizeable stones in it which have to be removed in order to obtain a homogeneous sample on which to conduct soil investigations. This is unfortunate because the field behaviour of a soil may be markedly affected by the presence of stones or large gravel. Some aspects of soil science, particularly those concerned with cultivation, require to be investigated on samples whose condition is as little removed as possible from that existing in the field. Chemical and similar analysis, which can only deal with small quantities of material, require sieved samples to ensure uniformity and for this purpose soil passing the 2 mm. sieve is the standard.

On digging with a spade, or turning over with one of the variety of mattock-like implements customary in plantation agriculture, the soil mass breaks into lumps. The size of these lumps, and whether larger or smaller pieces constitute the bulk of the sample, depends on the inherent soil type and on the condition of "tilth" in which the soil happens to be at the time of sampling. To give an adequate definition of tilth in precise terms is well-nigh impossible. A farmer or planter can judge tilth as a matter of intuitive experience. It is however compounded of so many factors that its scientific expression

is a matter of great difficulty. There are numerous measurements of soil characteristics that can be made, but even the better of them only cover a small part of the factors that are operative. The study of soil physics aims at disentangling the part played by individual factors and has been remarkably successful in this analytical aspect. The study of the interplay of the factors is much more difficult, and the fact that a generally accepted quantitative measure of tilth is not forthcoming shows that much more work will have to be done before we arrive at a reasonable understanding of the subject.

At its simplest the physical properties of a soil are dependent on the properties of the individual particles into which it can be dispersed, but the simplicity is more apparent than real. If a soil is treated appropriately the ultimate particles can be separated one from another. They will be found to be of varied size and still more varied shape. If the parent rock is crystalline, the size of crystals, the distribution of their cleavage planes and the hardness of the material will all affect size and shape. The previous history of the rock also counts tremendously. Water-borne particles subsequently compressed or cemented into rock will have sharp edges rounded off. Both size and shape will affect the manner in which particles are packed together in natural soil.

The large particles such as rapidly settle at the bottom of a vessel in which they are stirred with water retain largely the characteristics of the parent rock. The inner core remains virtually unaltered and they are covered with a film of weathered material. The smaller the particle, the higher the proportion of weathered, i.e. chemically



altered material will be, till finally the smallest particles will be fragments of the weathered material scaled off to form microscopic units of their own. Physical weathering causing diminution in size, and chemical weathering causing alteration in composition go on side by side and they both lead to important changes in the properties of the particles.

The Importance of the Surface of Soil Particles

Suppose a cube of material with a one-inch side is taken. Its six surfaces have a combined area of six square inches. If one side is divided into a hundred units and the cube sliced parallel to one of its other sides, the result will be one hundred plates one inch square and $\frac{1}{100}$ " thick. Each of these may by a similar process be further divided into a hundred strips measuring $1 \times \frac{1}{100} \times \frac{1}{100}$. A final division of these strips into a hundred equal prisms gives in the aggregate a million cubes each with a linear dimension of a hundredth of an inch. The surface area of the small individual cube is now $\frac{6}{10,000}$ square inches and a million of them have a surface of 600 square inches. The surface is increased in inverse proportion to the reduction in the linear dimension of the particle. As will be seen later some of the particles of the original sieved soil sample have diameters of 2 mm. whilst others have diameters less than .002 mm. If the fractionation resulted in cubes, the break-up of a single 2 mm. particle down to this lower dimension would increase the surface area of the material a thousand-fold. A single gram of soil, which can be easily heaped on to a silver threepenny piece, has a surface

of about 100,000 square centimetres, or about 50,000 times the area of the coin.

This increase in surface area plays a great part in the water retention capacity of a soil. When an impervious solid material is dipped momentarily in water it becomes wet, and after a certain amount of water has drained away there remains a thin film of water covering the surface. This water is held by the forces of surface tension until it more or less rapidly evaporates away. When into a soil, composed of large numbers of small particles with a large aggregate surface area, water is introduced, the enormous surface tension is capable of holding very large amounts in the pores between the particles.

Though the following chapter will deal more fully with the chemical properties of soil, one aspect must be mentioned here because it relates to that borderland between physics and chemistry in which so many soil properties lie. So-called chemical phenomena are influenced to a great extent by the physical conditions under which they take place. Materials which ordinarily speaking are not readily oxidised by the air (wood, paper, coal, etc.) are readily oxidised if the temperature is raised or their surface area largely increased. Flour and coal dust will spontaneously explode at ordinary temperatures if in a finely divided state. The changes which take place in the soil constituents, so far as we have considered them, are changes on the surface of particles. The large surface area exposed to air and water by minute soil particles speeds up the chemical reactions to which they are subject. Quite apart from any difference in chemical constitution, the smaller particles are the more reactive. Thus

whether we consider physical or chemical phenomena, the smaller particles of the soil are the most important in determining its fundamental properties.

The intensification of surface phenomena about which we have been speaking is characteristic of all substances in a very finely divided form. We are accustomed to think of substances such as sulphur which can exist in several states, solid, liquid, gaseous, or in solution. To these must be added another, the colloidal state which may be roughly defined as being between solid and solution, as far as the state of aggregation of the molecules is concerned, a "world of neglected dimensions". Most substances can exist in the colloid state which shares some of the properties of both liquids and solids. Tensile and other surface phenomena are marked in all substances in this condition which is why so many of them are sticky. (The word colloid is derived from a Greek word meaning glue.) The finest mineral particles of soil are sticky because these particles scale down in size to colloidal dimensions, and, when they reach this state, it is hardly possible to speak of soil as "inert".

Having then briefly indicated the part played by particle size in determining the properties of soil as a whole, it is not surprising to find that from the days of Sir Humphry Davy continual attempts have been made to grade soil particles into size categories, to improve the accuracy of such classification and to establish their relevance to soil problems.

Mechanical Analysis of Soil

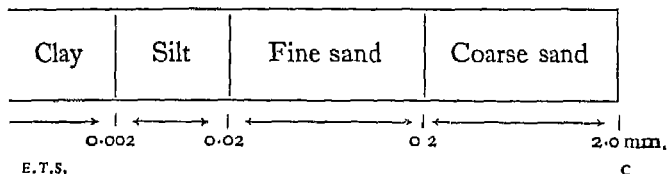
The process of grading soil particles is spoken of as "mechanical analysis". It is in many ways a highly artificial process and specially so in two ways. The larger and more solid particles of the soil are glued to each other and to the smaller particles by coatings of colloidal material some of it mineral and some of it humus (also colloidal) and its derivatives. Mechanical analysis concerns itself almost exclusively with that part of the soil which is present as sizeable particles and only to a lesser extent with the binding jelly. Consequently the first stage of the analysis is concerned with the destruction of the "cement". This involves treatment with acid, and the removal by oxidation of organic matter. This is carried out by heating with hydrogen peroxide. Even after this treatment the particles, if made into a suspension with water, would tend to cluster together or flocculate so, as an aid to further dispersal an alkali solution is added. It is evident that at this stage the material has been radically altered and is no longer soil in the primary sense.

The second artificiality arises from the method of grading. For the large particles sieves are used as the means of separation. For the smaller ones advantage is taken of the fact that if the material is shaken up with water the larger particles sink more rapidly than the finer ones. The problem resolves itself into formulating and using a physical law that indicates how long a particle of a given size will take to fall a given distance in a given fluid. Such a law is available in the so-called Stokes' Law which relates the rate of settling to the diameter of the particle and its density, and to the density of the suspending fluid and its

viscosity (i.e. the friction between the fluid particles). It should be noted that this law is formulated in terms of the diameter of the suspended particle and it is only exact for perfectly spherical particles. But soil particles are not perfect spheres and they are not all of the same density. If we calculate according to Stokes' Law that a particle two thousandths of a millimetre in diameter will fall 10 centimetres in 8 hours when suspended in water, we can set up a soil suspension in a vessel such that the surface of the suspension is 10 centimetres from the bottom, and at the end of eight hours we may say that all particles still in suspension are smaller than $\cdot 002$ mm. But that would only be true if all the particles were, or behaved as if they were, perfect spheres. Nevertheless the application of Stokes' Law enables an approximate picture to be drawn of the distribution of particle size in a sample of soil.

There are two standard methods of making a mechanical analysis, the complete sedimentation method and the sampling method. The former has fallen into disuse except in special circumstances, as for example when appreciable quantities of the various fractions are required for further examination, because it is long and tedious. It demonstrates the principle so well however that it is worth while to describe it briefly.

By common consent soil particles are now graded into four arbitrarily defined fractions. Their designations and size limits are shown in the accompanying diagram.



The limits of each grade are one tenth of the grade higher in the scale. The finest grade—"clay"—has no lower limit. The term "clay" as used in this connection is a specialised one. Clay in the ordinary sense has a large proportion of particles below 0.002 mm. and these give it its characteristic properties. But as used by brick, tile and earthenware makers, the particle sizes are not necessarily within the range quoted here.

The coarse sand is separated by pouring and rubbing the suspension through a standard sieve of the requisite mesh. Thereafter the suspension is set up as heretofore described in a beaker marked at 10 cm. above the bottom. At the end of 8 hours nothing but clay will be left in suspension and the contents are decanted into a bottle, care being taken that the sediment at the bottom is not washed over. The remaining sediment will contain some clay since particles with less than 10 cm. to fall will, during the 8 hours, have had time to settle too. These must be restirred into suspension, made up to the mark with water, allowed to stand a further 8 hours and the whole decanted again. By repeating this process about 30 times till the water after the 8-hour period is no longer turbid, all the clay will be collected in the successive decantations.

The suspension in the bottle is flocculated with acid so that it can be filtered, dried and weighed. It is usual to start with 10 gm. of soil and the percentage of clay can be calculated directly. A similar procedure is followed for the removal of silt using the appropriate time factor (4 minutes 48 seconds). The fine sand is left in the beaker.

The figures for the sands, silt and clay will total less than 100 per cent because account has to be taken of the

moisture in the air-dry sample, the loss of organic matter and the solution of some constituents in acid. These losses are determined as each operation proceeds and complete the schedule.

The sampling method is based on the same fundamental conception of settling velocities of the particles and consists in drawing off a measured amount of suspension in a graduated pipette at defined depths and at stated time intervals. From these samples the concentrations of the various soil fractions can be calculated after evaporation and drying. This method obviates the necessity for removing the whole of the fractions concerned and reduces the time involved from a matter of days to hours. As described here these methods are used to indicate the properties of the particles in the soil complex. They are in no way adequate descriptions of the details of the technique of mechanical analysis.

Some idea of the great variety of soil types judged from the mechanical analyses of the particles is given by the following examples.

TABLE I

Mechanical Analyses of Soils.

	(1) <i>Sandy</i> (Prescott)	(2) <i>Redbrown Earth</i> (Prescott)	(3) <i>Red Earth</i> (Ceylon)	(4) <i>Red Loam</i> (Prescott)
Coarse sand	21	2	46	4
Fine sand	71	45	21	10
Silt	2	35	6	29
Clay	6	18	27	57

As was previously remarked, mechanical analysis gives only a very limited and artificial account of soil conditions and the interpretation of such analyses is a matter of some

difficulty. Individual comparisons from soils of widely contrasting types are not very helpful. Although the fourth example has a high clay content it is nevertheless highly permeable to water and is loamy rather than clayey in working texture. The third soil is also porous. Its most noticeable feature is the small proportion of silt, a frequent feature of tropical soils. The finest particles of the soil are in the colloidal state and the apparently anomalous behaviour of the foregoing soils, viewed from the standpoint of particle size only, is due to variation in colloid type and behaviour.

Clay Minerals

The qualitative properties of clay have been intensively studied during the last twenty-five years making use of the powerful help afforded by the electron microscope and X-ray photography. It is now possible to construct a model of the manner in which the molecules of mineral substances allied to the clay are built up by the combination of atoms.

The dominant elements from which clay particles are constructed are oxygen, silicon, aluminium and iron. According to the proportions in which these elements combine, and, more important still, the arrangement of these atoms, different types of clay are formed, with properties, both physical and chemical, that depend on these patterns of arrangement.

The fundamental atoms in clay structure are of oxygen and these are laid down in sheets. The other elements take up their positions in the interstices between the oxygen atoms, hence the name crystal lattice given to the

pattern. Two main types of lattice pattern have been distinguished in minerals that make up clay. Kaolinite conforms to one type and Montmorillonite to the other.

As found in the field a clay particle is only exceptionally composed of a pure clay mineral. Taking into consideration the variation in proportions of the typical clay minerals and of the clay fraction itself in different soils, it is easy to see how greatly the properties of representative soils can also vary.

Swelling and Shrinkage of Soil Colloids

One of the most characteristic properties of colloids (such as gelatine, seaweed or soil) is the capacity for swelling when wet and shrinking when dry. Such changes can sometimes be seen on a grand scale in peat moors where under favourable conditions the convexity of the surface of the peat is easily detectable. In the laboratory it is easily demonstrated by packing soil in a porous cylinder or a similar vessel with a perforated bottom and noticing how the soil surface, cut level with the top when dry, pushes up on wetting above the edges like a slowly-filling gasometer. The higher the clay content the more the swelling, but apart from clay content, some soils swell more than others. On the whole tropical soils show only moderate swelling compared with temperate ones of similar clay content. As they swell, the soils imbibe water and that water becomes part of the structure of the colloidal particles. It is not free to move and is subject to neither gravitational nor capillary movement.

Those soils whose clay approximates to the kaolinite pattern are less prone to swell when wet and shrink when

dried than those whose clay is of the montmorillonite type. The reason for the difference is considered to be that the montmorillonite lattice has a construction that allows water to insinuate itself between the plates whilst kaolinite plates are not susceptible to such a concertina-like action. Their swelling depends upon imbibing water in strictly limited positions on the edges of lattice plates.

Soil in this condition has many interesting physical properties. The particles become bound together and the soil cannot be easily sieved. In the early stages of water uptake, it can be moulded or modelled in the fingers, without appreciably wetting them or sticking to them. Later on, at higher moisture contents, the soil becomes sticky and clings tenaciously to the hand or to any smooth surface such as a knife; and the change from the former to the latter state is quite marked and sudden. Finally, when still more water is added, it is not imbibed but bathes the particles so that they become lubricated and lose their plastic properties. The mixture is then no more than a soil paste.

The reverse process of drying is similar up to a point. The various stages of water-colloid relationships can be distinguished but they do not take place at exactly the same moisture contents. This is a fact of great importance both from the point of view of tilth and moisture relationships. The soil is not a sponge which can be put through a truly reversible process. Take a sample of soil at a given moisture content; wet it to saturation and then let it dry out till its former moisture content is reached, and you will have a sample that is substantially different in many respects from that with which you started.

A single wetting and drying will not produce in many soils a condition that can be recognised as different by mere inspection, but if the process is oft repeated, visible signs will develop. It may cake and form a hard cap on the surface and will crack. In addition, surplus moisture will drain away less freely, and even if some form of suction is applied it will be impossible to restore the original conditions. The reasons for this can only be explained in detail and quantitatively by conceptions of physics and mathematics that are outside the scope of this book, but the broad qualitative aspects are of the first importance too. They will be described here and their further implications will be dealt with later.

Soil Crumbs

The wetting and drying, swelling and shrinkage that take place alter profoundly the disposition of particles to one another in the soil mass. The colloidal properties that come into play in moist soil, rendering it, as we have seen, plastic and tacky, enable particles of various sizes, shapes and constitution to stick to one another in groups or crumbs. Between the particles of a crumb are small pores occupied by water and air. Between the crumbs themselves larger pores exist. In a normal soil in the field about half the volume is occupied by this pore space. In the process of wetting and drying, freezing and thawing there is a continual breaking-down and building-up of crumbs, and a continual readjustment and distribution of pore space. The quoted example involving alternate wetting and drying in the laboratory is a very extravagant example of weathering, and carried out in the way indi-

cated, the balance of events tends to break down rather than to build up the soil crumbs. The soil structure is impaired and tilth is destroyed. The important point is that good tilth and crumbs are closely related and that both are functions of the colloidal condition of the smaller soil particles.

The mechanism by which soil particles become aggregated into crumbs is still imperfectly known. The three components of soil crumbs are the clay mineral crystals, the inert non-colloidal fragments, mainly quartz, and organic residues degraded into humus.

Earlier in this chapter we spoke of breaking down the "cement" that held soil particles together and there, as here, the word requires inverted commas. Formerly it was considered that clay and humus formed a very intimate and significant complex but this is now questioned, though the clay colloids of soil may play an important role in protecting organic matter from biological attack. Since the presence of humus does not modify the swelling capacity of clay it is inferred that the individual clay crystals are not enveloped by it. Nor has the notion that hydroxides of iron and aluminium play a significant role in bonding soil particles received any support from experimental researches.

It is now suggested that organic matter links together *groups* of clay particles with other similar groups and with quartz crystals. The cohesive forces are the electric charges associated with the surfaces and broken ends of crystal lattice layers and also with humus and the exchangeable bases that form a kind of enveloping atmosphere.

These tentative hypotheses arise from work on temperate soils and they are not easily reconcilable with the known properties of many tropical soils. They do not offer a patently satisfactory explanation of the remarkable stability of crumb structure in some red tropical earths that are low in organic matter, high in iron and aluminium content and acid in reaction.

Water Movement in Soil

The question of how water moves in a soil is one of great difficulty and there is a danger of over-simplifying the problem in trying to describe it in untechnical terms. When rain falls on porous land it is absorbed and distributed through the soil. The lie of the land and the nature of the soil may be such that the water-table i.e. the zone of permanently saturated soil, may be near the surface. In that event if rainfall is heavy enough, some of the rain may percolate right through the soil and reach the water-table. On agricultural land unless it is low lying as in fen country, or under irrigation, the picture of water moving through the soil in quantity to a water-table is an unrepresentative one. More commonly rainfall penetrates the soil, is distributed in it, and is lost by evaporation or used by the plant before any fraction of it reaches a true water-table which may be far below the surface.

Earlier in this chapter we have considered the structure of the soil as showing a compact mass of soil particles of varying sizes gathered together in aggregates or crumbs of more or less stable nature. Between the crumbs and their individual particle-components are spaces of various sizes and shapes through which air and water circulate.

We have spoken of the great surface area of the soil particles. This surface is of course the containing wall of the soil pores and in relation to the total volume of the pore space that boundary wall is enormous. One cubic centimetre of pore space has a surface area of about a quarter of a million square centimetres. It is obvious that some of these pores are of very small dimensions and, viewed as channels through which water has to pass, they will admit of only very slow and restricted movement. Through the sizeable pores the movement will be relatively easy, especially if the pores are fairly full i.e. when the soil is nearly saturated. Under field conditions soil is seldom completely saturated: there will always be small quantities of air trapped in the pores.

The concept of soil water passing through a series of misshapen pipes (the interconnected pore spaces) is one which is only reasonably valid whilst rain is actually falling. At lower moisture contents, the water does not nearly fill the pore spaces. It is localised as films of varying thickness clinging to the boundary surfaces and held there by the surface tension forces active at the very large surface we have mentioned. Water movement is no longer directly through the pore centre but along the films. So long as these films are fairly thick, the movement is reasonably free. At still lower moisture contents the films are very thin indeed and for that reason water movement is very severely hampered. Moreover at low moisture contents the films are not continuous and the only way in which water can then move is in the form of water vapour.

Let us now construct an imaginative illustration of how

water moves into the soil when a relatively dry soil is wetted by a fall of rain. It might be thought that the soil moisture content would fall steadily from a state of near-saturation at the surface to a condition of near-dryness at some depth below. Experiments show that this is not so. The water front moves ahead leaving behind it a zone of substantially uniform moisture content with a value somewhere between that of saturation and what is termed "field capacity". Field capacity is the moisture content to which recently wetted soil settles down when no more "gravitational" water movement is possible. It is the state where water movement is by way of films rather than of channels. After rainfall ceases, the water front becomes blunted. Its movement is through films of ever-decreasing thickness and the moisture content falls rapidly. In this region capillary and other suctional forces come into play: the drier the underlying soil, the greater the suction exerted.

At the surface of the soil a similar falling off in moisture content is caused by evaporation. The water films thin out, the resistance to further loss becomes greater, and the surface soil becomes "self-mulched" and acts as a protective blanket to preserve the moisture status of the intervening layer. As water is slowly diffused or lost from these two boundary gradients the field capacity of the high moisture layer decreases. Under natural conditions this relatively stable layer of moisture is drawn upon by plant roots, and is more or less rapidly depleted. The important point is that the survival of plants through dry weather is dependent on these field-capacity layers which may persist for a considerable time below apparently dry

surface soil and which are quite independent of water-tables.

This picture of water movement is of necessity oversimplified. In few localities, even in the tropics, do seasonal rains abruptly end leaving soil moisture to be progressively diminished by plant transpiration from field capacity level to that state of dryness at which plants wilt. Intermittent rain creates new fronts that establish new horizons of soil at field capacity. If the supplementary rainfall is intense it may obliterate completely the residual traces of former field capacity layers. On the other hand it may only impose a superficial field capacity layer on top of horizons already showing signs of more or less marked depletion.

In those tropical zones where there is only one rainy season the creation of a deep zone of soil at field capacity during this season provides the only store of moisture for crops that are to remain in the ground during part if not all of the dry weather. A failure in the rains can then lead to difficulties extending into the next dry weather. An idealised representation of the course of events is given diagrammatically in Fig. 1. Each graph shows the percentage volume occupied by soil, water and air respectively at various depths under different circumstances. Diagram (a) depicts a soil at the end of the rains and at field capacity. It has three quarters of its pore space filled with water throughout the profile down to the vicinity of the water table. The dry season begins and the soil loses moisture at the surface by direct evaporation and at lower depths by reason of the activities of crop roots. In this way the water reserves may fall to one third of the amount present

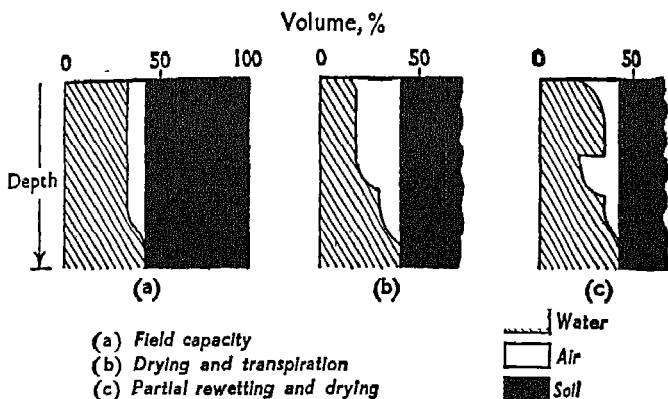


FIG. 1. Idealized cycle of changes in water content of a soil profile (after H. L. Penman).

at the end of the rains in those soil horizons where roots are prolific. Such a state of affairs is shown in diagram (b). If the ensuing rains fail either in intensity or duration the new water front may never fill the voids caused by the past dry season. The drying cycle starts again on this occasion earlier than is normal and may dry out the soil to a greater depth than ever. At best the growing vegetation is left with an isolated and limited layer of soil between two drier areas, which, quite apart from what the crop withdraws, is losing moisture at both margins (diagram (c)).

In these circumstances the vital question is to what extent can supplies from the saturated region of the water table supplement rainfall and mitigate the severe conditions imposed by the vagaries of the weather? Opinions on this possibility have varied considerably. The capillary rise of liquid exemplified by oil in lamp wick is familiar to

everyone and at one time the pores of capillary dimensions in soil were considered capable of raising moisture over considerable distances from regions of subsoil storage to the surface. Hoeing the surface was adopted as a method of disorganising these capillary channels and thus impeding a severe loss of moisture by direct evaporation. Later it was shown experimentally that the potentialities of this mechanism were grossly exaggerated and that on a short term basis upward movement of water in bulk from a water-table was limited to a distance of about 30 cm. in coarse sand and 80 cm. in heavy loam. The consequent reaction that set in led to a climate of opinion that dismissed upward movement of water as being agriculturally unimportant.

The movement of salts in irrigated soils has renewed interest in the movement of soil water, and it now seems possible, under favourable conditions, to move water as far as 250 cm. away from a water-table. The requisite conditions are that the soil should have a high proportion of pores of the right size, i.e. the size that, in the specific conditions will ensure that they are kept full. A break in the continuity of the water column disrupts the whole mechanism. These are very special conditions indeed, and to what extent they are generally reproduced in the field is a matter of speculation. The movement that has been demonstrated experimentally is very slow, and in all probability would be of minor importance in general. But in regions of periodic drought even small supplements of water from this source could be valuable. In irrigation schemes the effect in terms of salt accumulation over long periods may be of considerable importance.

Water Categories

In referring to water held in the soil, various descriptive terms are used. In the previous section the name "gravitational" water was used, and the word gravitational was placed between inverted commas. Other similar terms are "capillary water" and "hygroscopic water", the latter describing moisture which remains in association with soil when to the touch it is apparently dry. These terms are convenient, but their general use is acceptable if, and only if, it is realised that they do not separate soil water into clear-cut categories involving different types of forces for moisture retention.

In order to move water in a soil, or to remove it from soil, work has to be done and energy expended. If water is squeezed out of a sponge there is no doubt about the fact of energy being required to overcome the forces holding the water in the pores. If we start with a very wet soil it needs relatively little work to remove water, but as the moisture content falls and the water films become thinner it needs more and more energy to overcome the resistance of the water to movement. If in a graph we plot the moisture content of a soil against the work necessary to reduce that soil to various levels of moisture content the shape of the curve will be similar to Fig. 2. The point of importance is that there are no sharp bends or breaks in the curve corresponding to the limits of any of the usual water categories. One way of doing work on a soil is to place moist soil on a filter funnel and apply suction. Such suction is measurable, and by determining the moisture content of the soil with each increment of

suction, a part of the curve shown in Fig. 2 could be constructed. It is not possible to dry a soil completely by suction, but there are other ways of doing work on a soil-moisture system which allow of the curve being

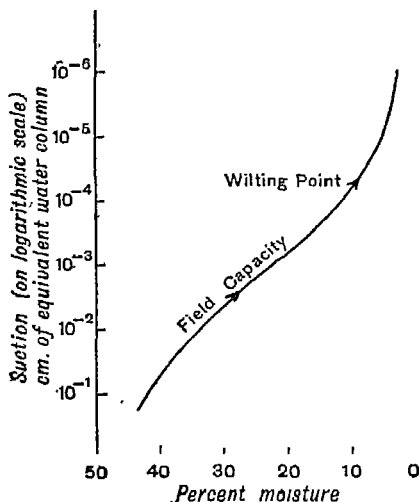


FIG. 2. Suction curve for a drying soil (after Schofield).

completed. Notwithstanding the fact that various means are adopted for doing work on the soil, the non-technical reader will not be far wrong if he envisages the work done throughout the whole range on the analogy of suction.

The concept of water retention and removal in terms of energy or work, provides a point of contact with the plant's use of water. When crops draw water from the soil through their roots, they do work. Eventually when the soil is nearly dry the energy that the plant can mobilise through its physiological processes and mechanisms is no

greater than that opposing it in the soil-water complex. Consequently the plant cannot get water: it has no effective suction gradient and it wilts.

If we constructed curves similar to that in Fig. 2 for a number of soils we should find that they were different in detail but similar in general type. In particular if we chose a definite value for the energy factor and read off on each curve the corresponding moisture content, we should find considerable differences between the values. Supposing that on each of those soils, the moisture content was determined at which a particular plant, growing in that soil, wilts. These values too would not be constant. The plant, it would be found, could maintain its water content on some soils when they were in a drier condition than others. But, if from the graphs the energy values corresponding to the wilting points are noted, they will be found to be alike within the limits of experimental error.

By energy methods we are thus able to measure the availability of water to the plant. For practical purposes these energy values must continue to be translated into ordinary moisture content figures.

CHAPTER III

THE CHEMICAL PROPERTIES OF SOIL

THE MINERAL PORTION

WE have already considered how important a part surface phenomena play in the physical properties of the soil. They are equally important in regulating the chemical properties. In this chapter we shall deal first with a type of surface action which has a great part to play in regulating the fertility of the soil, particularly as regards the retention of soil nutrients and the related property of soil reaction, that is, its condition of acidity or alkalinity.

Acids, Bases and Salts

It will be necessary to clear the ground by discussing simply the chemistry of acids, bases and salts. When chemical compounds were first studied systematically, the early chemists learned to divide many of them into two groups, the acids and the alkalis. The former were sour to the taste and corrosive in their properties. The alkalis were soapy in character and had the property of combining with acids to produce substances which were possessed of neither of the outstanding properties of their original components. These latter were called salts. This classification has proved to be too crude to account for the properties of all chemical compounds, but the fundamental characters remain distinguishable to a large degree. Closely allied to the alkalis which were prepared by

collecting the ashes of plants, were a number of other substances which had weaker alkaline properties and were insoluble in water. They were frequently prepared by heating metals, or compounds known to contain metallic elements, and were in fact the oxides of metals. These substances also had the property of neutralising acids. All such substances whether true alkalis, such as soda, or alkaline earths, such as lime, have been classified under the name of bases.

The fundamental property of an acid is that it contains hydrogen and that this hydrogen can be replaced by a metal or by the metallic part of a base. Thus hydrochloric acid, consisting of hydrogen and chlorine, will dissolve zinc releasing the hydrogen of the acid and producing a neutral salt, chloride of zinc, which can be isolated as a crystalline compound. If instead of elementary zinc, zinc oxide is acted on by hydrochloric acid, the hydrogen is still displaced by zinc but, instead of being set free as a gas, it combines with the oxygen of the zinc oxide to form water. This is a typical case of an acid reacting with a base to give a salt and water. Hydrochloric acid consists of one atom of hydrogen combined with one atom of chlorine. Some acids contain several replaceable atoms of hydrogen which can be replaced one by one. Complete neutralisation only occurs when the last replaceable hydrogen atom is accounted for.

An example of agricultural importance is phosphoric acid which contains three. In superphosphate a third of the hydrogen is replaced by calcium, but in the mineral phosphates all the hydrogen is replaced.

The association between material particles and electric

charges has been made familiar to everyone through the medium of radio and popular descriptions of the structure and architecture of the atom. Atoms and groups of atoms behave as if they carried electric charges when acids, alkalis and salts are dissolved in water. The combination of atom and electric charge is referred to chemically as an ion. Hydrogen and the metallic atoms that form bases carry positive charges, and other elements negative ones. In an acid, a salt, or an alkali the replaceable hydrogen and the basic elements carrying positive charges are balanced by other elements or groups which carry negative charges. Thus hydrochloric acid is $H + Cl^-$, sodium chloride, common salt is $Na + Cl^-$. As an example of an ion containing a group of atoms there is sodium carbonate, common washing soda $Na^+ (CO_3)^{--}$.

*Base Exchange**

The complex lattice structure of clay determines the distribution of the electric charges associated with the atoms of which the lattice is composed. The over-all balance is negative. In stable conditions these negative charges must be balanced by positive ones, borne either by ions of hydrogen or basic elements that are present in the dilute solution that bathes the particles of a normal agricultural soil.

In theory it is possible to envisage a condition in which all the negative charges of the clay colloid are balanced by hydrogen ions. Such a clay would be extremely acid since

* The term base exchange instead of cation exchange is used as being more intelligible to non-technical readers.

the degree of acidity of a substance is measured by the concentration of hydrogen ions. In practice this state of balance never happens. In natural conditions there is always a choice of positive ions and the equilibrium attained will reflect that diversity. Even if a soil is thoroughly leached with an acid to remove bases absolute finality is never reached, for a clay with its negative charges absolutely saturated with hydrogen ions is unstable. Clay particles are rich in aluminium and in highly acid conditions this is present in ionic form. The balancing of the negative clay charges is then performed by aluminium ions and the acid clay becomes an aluminium clay rather than a hydrogen clay.

At the other end of the range it is possible to produce sodium or calcium saturation by treating the clay with the appropriate solutions. The generalised picture that emerges is of a soil whose clay fraction can remove basic ions from solution and hold them in close, but not very tenacious, association at the surface of the particles. In accordance with the circumstances already described these bases can be replaced by others. The whole process is described as "base exchange" and it is quantitative, (i.e. the exchange is ion for ion and hence atom for atom. The exchange obviously alters the chemical constitution of a soil. Physical properties are also changed. Calcium saturated clay soils are easily worked and drained but sodium clays are sticky and of low permeability.

From the foregoing it is obvious that the total amount of exchangeable bases present in a soil will depend upon the amount of clay it contains and the degree of saturation with bases, i.e. the extent to which the negative charges have been balanced by positive basic ions. In addition the

total number of charges to be neutralised must be considered. Some clays have a greater base exchange capacity than others. The montmorillonite group have this property more strongly developed than the kaolinite clays. In so far as exchangeable bases contribute to the supplies of available nutrients this greater capacity gives montmorillonite soils a potentially higher level of fertility than kaolinites.

All operations in cultivation and manuring (with which is included liming) disturb the equilibrium between the unchanged core of the soil particles, the skin of colloidal material where base exchange phenomena occur, and the soil solution in which they are bathed. Their purpose is to alter that equilibrium in a manner favourable to the soil as a medium for plant growth.

One of the features of base exchange that is of great importance is the rapidity with which it occurs. Given suitable conditions it is instantaneous. By suitable conditions we mean a high concentration of the ion that enters, and adequate mechanism for the removal of the displaced ion, for, if the original ions are not removed by drainage they compete with new entrants and an equilibrium condition is arrived at.

In the foregoing the tacit assumption has been made that the new ion is introduced by means of a solution. But when an ion is exchanged, the new entrant is taken out of solution and becomes absorbed and bound to the acidoid complex. It has entered into a new state and is no longer soluble in the ordinary sense. The ion that is displaced goes into solution and that is why it can be removed by leaching with tolerable rapidity.

Fertiliser Retention

All this may sound highly theoretical but it has important practical applications in the realm of plant nutrition, practical manuring and the control of soil acidity. Consider for a moment what happens to an artificial manure such as muriate of potash (potassium chloride) or sulphate of ammonia. Both are highly soluble. Water will dissolve a third of its weight of the former and nearly three quarters of its weight of the latter. There is consequently a fear in the non-technical mind that if these are used as fertilisers they will rapidly be washed out of the soil. Small as are the quantities used in agricultural manuring, they come into contact with the soil in sufficiently high concentrations for their basic ion to disturb the balance of the absorbed hydrogen and other bases. They enter the soil complex by the process of base exchange and are fixed there. The complex of one atom of nitrogen and four of hydrogen which forms the ammonium ion is one of the groups of atoms previously described as forming ions and it behaves as a metallic ion carrying a positive charge.

How quickly this process, base exchange, is carried out can be demonstrated in any laboratory where a glass tube is packed with a clay soil and a weak solution of ammonium sulphate poured through the soil column. It takes but seconds for the solution to percolate. If equal volumes of the original solution and the percolate are then treated with Nessler's reagent which gives a yellow-brown colouration to solutions containing ammonia compounds, that which has percolated will be seen to be very much lighter. Allowing for the quantity which travels down the

inside of the tube without contact with soil, and for the impossibility in such a demonstration of bringing every ammonium ion into contact with the reactive surface of the soil colloid, it is a fair inference that the reaction is instantaneous. If subsequently the soil is percolated with water only, it is found that the ammonium fixed by base exchange is not readily washed out. The fact that nitrogen is lost from soils manured with ammonium sulphate, is due to changes which occur subsequently and their operation will be considered later.

Soil Reaction

The greater the extent to which the ionic exchanges of the clay particles are dominated by basic ions to the exclusion of hydrogen and aluminium the less acid a soil becomes. Although it is practically convenient to speak of soils or other materials as being acid, neutral or alkaline, the division into these categories is to some extent artificial. It is more convenient to consider the whole range from high acidity to high alkalinity as a single range dependent on one factor, the concentration of hydrogen ions. We can then speak of soil "reaction" and express it quantitatively in terms of hydrogen ion concentration. In the tropics agricultural soils may show tremendous variability in hydrogen ion concentration, those at one end of the scale being ten thousand times greater than at the other. Such a scale is too cumbersome to use so in practice it is telescoped by converting it into a logarithmic scale or scale of indices. $100 = 10^2$ $1,000 = 10^3$ $1,000,000 = 10^6$, where the 2, 3 and 6 are indices or logarithms based on the unit 10. Actually hydrogen ion

concentrations are small and the H ion concentration of water is 10^{-7} which expressed in ordinary terms is $\frac{1}{10^7}$ or $\frac{1}{10,000,000}$. (The ionic concentration is expressed as grams per litre (1,000 c.c.) but at the moment the units are immaterial.) A highly acid soil might have a concentration of $\frac{1}{10,000}$ or 10^{-4} . Its "acidity" would therefore be a thousand times as great as that of water. The so-called *pH* or reaction scale is the scale of these indices without consideration of their arithmetical signs which are always negative. It thus follows that we should report the *pH* or reaction value of water which is neutral as *pH*7 and of the highly acid soil as *pH*4. Alkaline soils would have values higher than *pH*7. Notice that a difference of one unit in the scale represents a difference in hydrogen ion concentration of ten times, two units a hundred times and three units a thousand times, which is the ratio arrived at previously between 10^{-7} and 10^{-4} . Because no attention is paid to the negative sign an *increase* in hydrogen ion concentration or acidity is shown by a *decrease* in the *pH* value and vice versa.

The fundamental methods by which the hydrogen ion concentrations are determined are too abstruse to be dealt with here, but rapid and approximate methods are frequently used in soil work. Many organic chemical substances vary in colour at different *pH* values, sometimes changing suddenly at a given hydrogen ion concentration, for example from yellow to red. Such an "indicator", or a mixture of several having different colour-changing points, provides a range of tints that indicate the approximate

reaction values when shaken up with a suspension of soil and water. Simple outfits of glassware and indicators are marketed by most firms of analytical chemical manufacturers.

The change in reaction which the addition or subtraction of a given number of basic ions makes in a soil is not the same for all soils. Very little leaching of a light sandy soil by an acid solution will change its reaction markedly but on a heavy clay or humus soil the same treatment would have relatively little effect. This resistance to change is spoken of as "buffering", and a soil which only slowly changes its reaction when treated with acids or alkalis is said to be well-buffered. Buffering is not confined to soils. Quite simple chemical compounds show it, but the explanation given by chemists for buffering of solutions cannot be used in all its relative simplicity to account for what happens in the more complex case of soils. That being so, it is not profitable to enter here into the technicalities of even simple cases of buffering, except to note that the quantity of colloid and its type determines the degree to which buffering occurs. The property of buffering is highly important because well-buffered soils are less subject to fluctuations in reaction caused by climatic and environmental factors. Of course it works both ways. A good fertile soil of suitable reaction, well-buffered, will not easily be changed for the worse. Conversely a very acid or alkaline infertile soil, also well-buffered, will need drastic treatment to bring it into good order.

Soil Salinity and Alkalinity

Soils highly charged with soluble salts occur in many parts of the world. This condition may be brought about

owing to inundation by the sea as in the kwelders of the Netherlands, or more generally in arid regions where evaporation exceeds rainfall and where salts may be continually added to the subsoil water by seepage from extensive areas at higher altitudes. Vast river systems traversing low lying plains, e.g. the Indus basin in W. Pakistan, are particularly liable to create saline conditions in the regions through which their rivers flow. Saline soils reduce the productivity of crops growing on them because the plant has to do more work in order to get water from them than from normal soils. Accordingly the types of crop that can be grown on saline soils is restricted, and in localities where salinity is excessive agriculture becomes impossible and desert conditions supervene.

The soil solution that bathes soil particles is necessarily saline to a small degree but in the wet tropics the possibility that toxic concentrations will occur is remote because the soluble constituents are carried away in drainage water to the water-table below the root range and are discharged in springs and streams without any harmful effects. In low lying and desiccated regions the upward movement of water that was discussed in an earlier chapter, coupled with a high rate of evaporation and plant transpiration, will concentrate the salt in the surface soil. Because of deficient rainfall this undesirable salt content is not reduced during the limited rainy season by being washed down deep enough to be beyond the root range of crops. It remains and increases in quantity till finally, as mentioned heretofore, the soil is rendered unproductive.

Salinity and its more devastating successor alkalinity have developed over large areas owing to ignorance of the correct technique for successful irrigation. The Punjab was not troubled with salt accumulation in the first three or four feet, i.e. within root range of the average crop, until irrigation was started. It was ignorance of the principles of base exchange that brought about the disasters associated with black alkali soils in the Sudan and the Indian sub-continent. Correspondingly the removal of that ignorance as a result of soil investigations in Russia, Holland and U.S.A. has made it possible to prevent increasing damage and to reclaim soils adversely affected.

Alkalinity is particularly associated with soils that are comparatively high in their content of both calcium and sodium. The former is more readily removed from the exchange complex and hence the proportion of exchangeable sodium is augmented. The sodium impregnated soils tend to deflocculate with a consequent decrease in soil permeability. This in its turn impedes drainage so that salt accumulation is accentuated and a vicious cycle is established. The soil becomes not merely saline but alkaline and incapable of bearing crops.

The fundamental cause of soil deterioration under irrigation is incorrect application of water. Accumulating salts must be washed down to levels not drawn on by plant roots. This demands that the soil be kept permeable and the presence of some salt in irrigation water is not inimical to this. Frequent applications of too little water brings no relief. Leaky water-courses, by increasing the hydrostatic pressure, raise the water-table over areas in close proximity. Irrigation from wells avoids this danger whilst

periodic flooding, as an alternative to continuous irrigation, reduces and may even eliminate the hazard of alkalinity.

Since these catastrophic changes in soil constitution are caused by the base exchange substitution of sodium for calcium, rehabilitation demands the reversal of the chemical reaction. The first requirement is a reduction in soluble salt content. This can be effected by lowering the water-table and increasing the efficiency of drainage even at the cost of pumping out water by means of tube wells. Secondly, calcium in the form of gypsum is applied in quantity and ousts the sodium. Gypsum is superior to calcium carbonate because of its greater solubility and also because the sodium expelled from the clay complex is taken into solution and washed out as neutral sodium sulphate instead of alkaline sodium carbonate. Deflocculation is thereby avoided. The success of this treatment depends upon the meticulous regulation of the water supply. The employment of water that is to some degree saline is no disadvantage because in the presence of calcium the salinity will promote flocculation of the soil and therefore encourage free drainage without bolstering up the exchange sodium.

CHAPTER IV

THE CHEMICAL PROPERTIES OF SOIL

ORGANIC MATTER AND HUMUS

HUMUS to the chemist is the final product of the disintegration of the organic substances of plant and animal tissues, but to the gardener and agriculturist it means a whole range of products between the raw material and humus proper. It will be convenient therefore to say something first of all about the processes that bring about this decomposition, particularly as recent work indicates that the by-products and intermediate products play an important part in determining both the structure and the fertility of soil.

It has already been pointed out that in an agricultural sense soil does not exist until it contains decomposing organic matter. Whereas the mineral particles of rock are changed mainly by direct chemical and physical agencies, vegetable and animal tissues are broken down by the activities of living organisms. To put it in a different way: the chemical changes that take place are dependent on life processes. Worms of various sorts and insects, particularly ants and termites in the tropics, play a not inconsiderable part in the disorganisation of organic matter, but the major part of the work is done by microscopic fungi and bacteria. The mineral structure of the soil is their home, but since their presence is so essential we can rightly say that they form an integral part of a

soil's constitution. The term "living soil" is no far-fetched description but a plain statement of fact.

The Raw Materials of Soil Organic Matter

Organic matter is mainly composed of four chemical elements, carbon, nitrogen, hydrogen and oxygen. Sulphur and phosphorus are also quite prominent constituents but broadly speaking carbon and nitrogen play the most decisive roles.

The most important compounds formed from these elements and found in plant tissues (which contribute most of the organic matter in soils) fall into three groups:

- (1) The carbohydrates and associated compounds which contain carbon, hydrogen and oxygen.
- (2) The lignin group, very different in chemical properties and constitution but also containing, according to the latest researches, carbon, hydrogen and oxygen.
- (3) The proteins which in addition to the former three elements also contain nitrogen.

This order corresponds with the relative abundance with which these substances are found in plant tissues as a whole. They may be listed in another way corresponding with their ease of decomposition. In such a classification lignin falls far behind either of the others.

The carbohydrates include cellulose which forms the basis of the cell-wall structure of plants, as well as storage products such as starch and sugars. Lignin is the name given to a rather indefinite group of substances which provide the rigid structural framework of plants and become interwoven with and encrusted on the cell walls.

Wood is very highly lignified. The proteins are prominent as the chief constituents of the cell contents.

The elements from which these substances have been built up have originally come from the gases of the earth's atmosphere, in the form of carbon dioxide, nitrogen and water vapour. By the continual processes of life, death and decay, they become embodied in living tissues and finally return whence they came.

Although the decomposition of organic matter in the soil has received a great deal of attention, and the science of microbiology is now one of the most important branches of soil study, there is still no unanimity of opinion as to how the residual material humus is produced. One school of thought believes that humus is a degradation product of the highly resistant lignin and that this group of plant tissues is the only one concerned. In opposition to this view another school holds that before humus can be formed the decomposition products of crude organic matter have to be built up into microbial tissues, and that it is the degradation of these tissues that produces humus.

This is not the place in which to trace the evolutionary processes by which the present economy of nature has been achieved; we shall deal only with things as they are.

The Carbon and Nitrogen Cycles

Carbon is abstracted from the atmosphere in the form of carbon dioxide by green plants whose colouring matter, chlorophyll, uses the sun's energy to build up more complicated and energy-storing compounds. The synthesis of carbohydrates and proteins takes place in the leaves and other green parts of plants.

A small group of bacteria living in the soil has the capacity to use gaseous nitrogen as its source of this element, and many species of one family of higher plants, the Leguminosae, have associated with them other bacteria which are not free living, but which have the same property. Some mineral compounds of nitrogen are present in rocks formed in geological ages before plant life appeared on earth but these are not of wide distribution. Hydrogen and oxygen are ubiquitous in the form of water.

Whilst plants (including micro-organisms) are living and growing they are accumulating and immobilising chemical elements: when they die and decompose they release them. In the cycle of processes that takes place, organic matter, as known in the soil, occupies a place in the disintegrative part of the cycle. Micro-organisms for the most part require their carbon and nitrogen in a complex elaborated form and they acquire it from the dead tissues of the higher plants which have the power to use simpler forms. What for the tissues of higher plants is destructive, is for them a building-up process. Being unable to use sunlight as a form of energy, they are dependent on organic remains both for food and energy. Energy they derive from the oxidation of carbon; food predominatingly from the nitrogenous compounds of protoplasmic protein.

When micro-organisms are supplied with adequate food and energy supplies, they multiply rapidly. Because of the high proportion of carbon in the plant tissues their energy supplies are assured and multiplication proceeds until shortage of nitrogen applies a brake. The whole

tempo is then slowed down, being dependent on the death of more plants or micro-organisms to continue the never-ending cycle.

Viewed simply from the point of view of a micro-organism (if micro-organisms can be said to have a point of view), the economy is never perfect. The carbon is continually converted into carbon dioxide which is of no further use till it has been transformed again by higher plants and sunlight. The nitrogen compounds disintegrated by fungal and bacterial activities do not by any means balance perfectly their needs, and any excess becomes available in simpler forms for the maintenance of higher plants which can use it for their nutrition. The carbon and nitrogen cycles are thus seen to be divisible into two phases, one of synthesis by higher plants and one of destruction by the soil organisms.

The foregoing is a very skeletal account of a long chain of complicated processes, and the release of carbon and nitrogen by micro-organisms does not occur with uniform speed at all stages. The fungi play the most important part in the first stages and the bacteria operate in force later. There are hold-ups due to the accumulation of substances which are not easily attacked by either. Carbohydrates and proteins are easily broken down, but lignin is very resistant. There are important gaps to fill in. The successive breakdown of proteins produces simpler substances till eventually ammonia and its salt derivatives are formed. From what has been said formerly it might be thought that since ammonium ions are so readily fixed by colloidal soil particles an appreciable accumulation of ammonia would be found in the soil. If this were so it

would kill most plants. Actually, the quantities of ammonia found in the soil are very small; for there are bacteria which oxidise it to nitrite, and others which then carry the process still further to nitrate. In ordinary soils, the nitrite-nitrate transformation is the quickest of all and the detection of nitrite in agricultural soil is a very delicate analytical procedure. In fact, if any quantity is found it is a sign that agriculturally something is wrong.

Under some conditions nitrate can be converted into elementary nitrogen and fail to complete its normal cycle through green plants.

The processes of nitrification and denitrification though diametrically opposed can proceed simultaneously in the soil mass if aeration is patchy. A water-logged soil is poorly aerated and denitrification readily occurs in saturated soils. It is now clearly recognised that chemical reduction of nitrates occurs long before the saturation point is reached. The critical moisture content above which denitrification is liable to occur has been put as low as sixty per cent of the water-holding capacity of a normal soil. Since nitrates are all readily soluble they can be removed by drainage and in this way become a complete loss. In other circumstances elementary nitrogen appears to be released from decaying organic matter, when it is present in bulk and is subject to alternate wetting and drying. Most of these changes can be given a logical setting diagrammatically as in Fig. 3, which shows the cycles for nitrogen and carbon (very much simplified) divided between the two phases of destruction by micro-organisms and synthesis by green plants. The special case of the association or symbiosis of green plant and

nitrogen-fixing bacteria occupies a place on the dividing line.

From this diagram it is clear that the destruction of

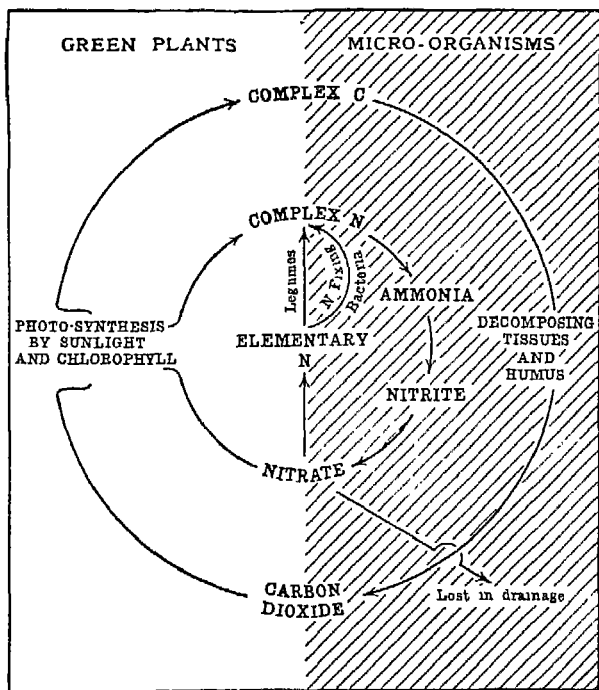


FIG. 3. The Carbon and Nitrogen Cycles.

carbon-nitrogen compounds releases nitrogen in progressively simpler forms and that what is not quickly made use of by the green plants is lost. Conversely, the only manner in which nitrogen can be immobilised and conserved is by uniting it with carbon. This provides an

added reason why the maintenance of organic matter in soils is of such prime importance. The practical aspects of this process will be dealt with later in the chapter on green manuring and composting.

In the process of microbial decomposition plant remains lose large quantities of both carbon and nitrogen and the rates at which these losses take place depend on the composition of the raw material. Eventually by the time the plant debris is reduced to humus the proportion of carbon to nitrogen is relatively constant.

In temperate climates the carbon-nitrogen ratio is stabilised at a value between 10 and 12 but in tropical soils the figure is much more variable. Values as high as twenty have been recorded for some soils carrying high grass savanna. There is a tendency for soils of low pH value to have higher than average C/N ratios. Whatever the equilibrium point to which the ratio moves, further decomposition results in the simultaneous loss of carbon and nitrogen in balanced proportions. This illustrates once again the fact that it is useless to replenish a soil with simple nitrogenous compounds and expect its permanent fertility to be enhanced, unless steps are taken to replenish the carbon content also. Since carbon is continually being lost from agricultural soils by the steady drain on resources through oxidation to carbon dioxide, in actual practice the problem of nitrogen conservation is translated into a problem of carbon conservation. Within reason, it may be said "Take care of the carbon, and the nitrogen will take care of itself."

Before leaving the subject of microbial activities in the soil we must return to the conception of crumb structure

dealt with in a previous chapter. The division of soil properties into physical, chemical and microbial is merely a convenience for purposes of exposition. Their interrelation is close and vital.

Organic Matter and Soil Structure

We have previously mentioned that colloidal material lies at the root of crumb structure and that "humus" is the crumb builder *par excellence*. This was a general statement which needs expansion. What part does finished humus play in crumb building? What part, if any, do the intermediate stages between the only slightly decomposed plant tissues and the finished product play? The old view tended to emphasise the part played by humus proper, but in the course of experience this view was seen to lead to certain anomalies especially in some tropical soils. The black peaty bheel soils of the Surma Valley in N.E. India lose their texture after continuous cultivation. They become fluffy and hard to wet. Though they still contain much more humus than the average tropical soil, they lose fertility more noticeably than other apparently poorer soils. The bheel soils are reconditioned by digging out sub-soil and using it as a top dressing. In Ceylon a not dissimilar but thinner top soil in the uplands becomes powdery and dries out more quickly than the red-brown soils of lower organic content but of otherwise similar mechanical composition. These are but instances from a considerable number of observations which, coupled with laboratory investigations on soil organic matter, have suggested that the intermediate products have an important part to play. What seems

particularly vital is not the total amount of organic matter in a soil nor even its true humus content, but the amount of readily decomposable material and the rate at which it breaks down. Some light is thrown on this by watching the processes that go on in a heap of decomposing vegetation. Three broad stages are noticeable, that during which the mass is being rapidly decomposed with evolution of heat, an intermediate stage in which the material assumes a very sticky consistency, and a final stage characterised by the less sticky and more crumbly texture of leaf-mould. The stickiness of the middle stage is due to a mucus, formed by bacterial action, that follows the initial breakdown of tissues by fungi. It is probably formed from the fungal tissues themselves rather than from a mere by-product of the decomposition of higher plants. The stickiness of this mucus can quite easily be measured by sandwiching the material between two smooth metal plates and measuring the force necessary to separate them. Experiments with various decomposing materials have shown that a gravitational pull of over 1,000 gms. ($2\frac{1}{4}$ lb.) per square centimetre is necessary to overcome the mucus adhesion. It seems highly probable that this mucus is the main organic factor in soil crumb formation and that the balance between its rate of formation and rate of disappearance is closely connected with the maintenance of crumb structure in despite of destructive weathering processes.

Experiments have shown that crumb structure was more rapidly achieved in soils to which raw fermentable residues were added than in those which received the corresponding products of decomposition. If this is the case, the

emphasis on humus is shifted from the static end-product to the dynamic processes themselves.

It is very difficult to draw a sharp distinction between the beneficial properties of humus proper and those of degenerated organic matter. Chemically humus is not a fixed and definable compound. By using various solvents this or that fraction of the humus complex can be extracted, but there is always an insoluble residue left which it is impracticable to separate completely from the clay colloids. Though the more recondite aspects of humus composition are still unresolved its effective and practical properties are well known and authenticated. The fact that the base exchange capacity is greater than that of clay has a bearing on its influence in controlling soil structure and hence on aeration, water-holding capacity, drainage, swelling and shrinkage. Its regulatory function in nutrient supply will be discussed in a subsequent chapter.

The amount of humus in a soil depends upon the balance achieved between contending forces of accumulation and wastage. The whole environment, including soil type, ecology, meteorological factors, topography and human interference, plays its part in determining that balance. In so far as the evidence available is consistent, the most potent factors are rainfall and temperature. High rainfall and low temperatures are conducive to the conservation of organic matter and humus.

CHAPTER V

THE AVAILABILITY OF SOIL NUTRIENTS

IN the foregoing discussion of the physical and chemical properties of soil attention has been drawn to the important part played by clay minerals and organic matter, with its end product humus, in regulating soil processes. In the course of this exposition nutritive elements have been referred to in a general way. Their availability to growing crops is of paramount importance. This chapter is therefore devoted to the consideration of some of the soil processes that regulate the availability of the main nutrients concerned in plant growth.

Nitrogen

The store of soil nitrogen, built up and dissipated in accordance with the pattern of the carbon-nitrogen cycle, is present largely in the form of disintegrating proteins that constituted the cell contents of higher plants and micro-organisms. Since the higher plants cannot assimilate organic nitrogen they are dependent on the simpler products formed during decomposition. The amount and regularity of the supply depends to a considerable extent upon the rate of that decomposition. Though faulty agricultural methods can rapidly dissipate organic matter, it is nevertheless true that, when undisturbed, moist organic matter is not decomposed at a catastrophic rate even in the tropics. Swift decay depends upon the

coincidence of a number of factors favourable to the activity of micro-organisms responsible for the decomposition. Chief of these are adequate supplies of food and energy material and correct moisture relations. In the chapter on Green Manures and Composts these matters will be discussed in detail.

The generation of readily available mineral nitrogen is intimately connected with the cycle of moisture changes that goes on continuously in soil. The decisive feature is the alternation of dry and wet periods. In the tropics, because of the prevailing high temperature, even minor breaks in the rains can rapidly dry up the surface soil to which micro-biological activity is largely confined. In this dessicated condition micro-biological activity is low. After a spell of dry weather a moderate rainfall stimulates the organisms and rapid decomposition ensues accompanied by the production of a flush of nitrate. If the soil remains moist for a considerable period the flush of nitrate diminishes to a low level. Eventually further activity is halted by a renewed dry spell. Both laboratory and field experiments present substantially the same generalised picture of what happens. Alternating peaks and hollows in the moisture content graphs correspond to related variation in nitrate production.

This available nitrate can be largely lost if heavy rain storms wash the nitrate reserves into subsoil depths beyond the range of plant roots. Unlike the ammonium ions, those of nitrate are not immobilised by exchange reactions. Nevertheless some nitrate is retained by soil of good structure. The mechanism of this retention is as follows.

In the degradation of organic nitrogen to nitrate a precedent stage, which is normally short-lived, produces ammonium ions which are absorbed on the clay complex. Oxidation to nitrate thus takes place in the heart of the soil crumbs where at field capacity the moisture exists in thin films. The nitrate associated with these tenacious films can only be released by the slow process of diffusion into the wider channels where roots ramify. Certain plants that tolerate acid soils can make use of ammonium compounds directly, thus avoiding to some extent dependence on the vagaries of nitrate production.

Two important principles in soil management emerge from this consideration of nitrate production and loss. First that good husbandry requires that land should be prepared for and sown early enough for the crop to take advantage of the early nitrogen flushes following the dry season. This of course means taking a risk and exercising judgment when the first tentative showers occur before the full onset of the rainy season. In the second place it is very necessary to grow crops of adequate stand so that the soil mass is penetrated by a root system capable of using the nitrate flushes before they are washed down in drainage.

Phosphate

The availability of phosphates has been a much debated subject since the early days of agricultural research when Sir John Bennett Lawes converted the insoluble phosphate of bones to soluble monocalcium phosphate, the principle form in superphosphate. Those phosphates that are soluble in any degree change into less soluble forms more

or less rapidly when in contact with soil. One of the consequences of this reversion is that the soil solution in equilibrium with the soil particles has normally a low concentration of phosphorus. This limitation in phosphate availability is reflected in the well-established fact that no more than thirty per cent of phosphate added to the soil as fertiliser appears in the tissues of succeeding crops.

It is therefore not surprising that numerous attempts have been made to measure the available phosphorus in both soils and fertilisers. On an empiric basis the most successful of these has been Dyer's two per cent citric acid extraction. In so far as this solution is intended to simulate the solvent action of soil acids there is a measure of plausibility in its use because decaying organic matter does give rise to citric and other analagous acids. Nevertheless no chemical extractants can do more than provide a rough estimate of the pool of phosphorus compounds that is available to the plant at a given time. It does not follow that because the phosphorus is in a form that is virtually unextractable by laboratory reagents, it is entirely useless to a growing crop.

Soil phosphorus is usually combined with calcium, provided that the calcium status of the soil is reasonably high. When the soil is acid the phosphorus will be increasingly in combination with iron and aluminium. In the tropical red earths, low in bases and high in oxidised iron and aluminium, this type of association may be predominant, in which event the phosphorus availability may be low. Where a soil supports, or has supported, a good covering of vegetation and has a profile well supplied with organic matter there will also be organic phosphorus

compounds in considerable quantity. In view of the low calcium status of the red earth soils of the wet tropics, the only available phosphorus in these soils may well be that derived by the mineralisation of the organic phosphate reserve. This phosphate is released *pari passu* with nitrate in the alternating wet and dry phases of disintegrating organic matter.

For all nutrients in the soil there is at any particular time an equilibrium between the "available" and "non-available" supplies. Availability to the plant is determined not merely by the magnitude of the easily assimilable portion, as measured by the concentration in the soil solution, but by the speed at which it can be renewed when withdrawn by the crop or leached out in drainage water. To use a homely simile, when we are hungry the satisfaction of our appetite depends not only on what is at hand on the table, and more remotely in the larder, but on how quickly the former can be replenished from the latter. There is a labile pool of nutrient in the soil the contents of which are in continual migration between the soil solution and the solid phase of the soil particles. Extraction methods measure this pool in a manner corresponding to the measurement of water in a tank by draining its contents and ascertaining the volume. The availability of what is in the tank (or pool) depends also on a further factor, the pressure or potential of the supply. So long as only one type of soil and one method of extraction are under consideration an extractive method works reasonably well for comparative purposes on a particular crop.

On different soils the relationship between potential

and capacity is variable and the interpretive value of extraction data as a measure of availability breaks down. The phosphate problem in particular needs further clarification before a practical availability yardstick can be recommended for general use with any degree of assurance. Now that it is possible to trace the movement of elements from soil to plant by employing radioactive forms the problem of availability is being tackled by this new and powerful method. There are indications from recent research that reversion and fixation of phosphate in the soil is not agriculturally such a bogey as it was considered to be twenty or thirty years ago. But this more optimistic outlook is not too relevant to tropical soils profuse in iron and aluminium in a highly oxidised state, and rich in iron concretions that occlude phosphates.

Potassium

The discussion of base exchange phenomena in Chapter III carries the inference that exchangeable bases, of which potassium is agriculturally one of the most important, provide ready supplies of plant nutrients. Exchangeable potassium is a constant component of the labile pool of nutrient mentioned in the previous section. But as in the instance of phosphorus assessment of the supply in the labile pool is not an infallible guide to potash availability. Nor is the determination of the exchangeable fraction.

Fixation of potassium takes place in varying degrees in all soils. It is associated with the clay fraction and not with organic matter and it is less prevalent in kaolinitic than in montmorillonite types of soil. The degree of fixation is affected by a number of circumstances. Inten-

sive drying of soil is a potent instrument. So is the presence of other ions normally found in soils. In ascending order chloride, sulphate and phosphate ions influence this fixation.

This fixation however has not the permanence that is attributed to phosphate fixation, and plants are able to make use of the non-exchangeable fraction of the labile pool.

Other Nutrients

The available fraction of a nutrient is of necessity the most susceptible to loss by drainage, and that applies especially to nutrients in the process of base exchange. We have seen that the continued high concentration of a single base can, in circumstances of faulty irrigation, displace all or most of the other exchangeable ions. On a much less significant scale extravagant manuring can produce a similar effect especially in tropical soils whose reserve of bases is small. There is always the possibility that a dangerous situation will arise as regards minor elements. The combination of lavish fertiliser doses and greater removal of trace elements in augmented crops may in due course deprive the crop of an essential nutrient and thereby limit yield. For example, a soil high in exchangeable potassium is likely to have only a moderate or low content of magnesium.

Circumstances sometimes arise in which a soil not intrinsically deficient in a nutrient has the supply so locked up that it is almost completely unavailable. High fluorine contents, such as are encountered in some Kenya soils diminish phosphate availability by the formation of

relatively insoluble fluorapatites. Organic matter immobilises copper and the resultant deficiency has had serious consequences on crops in the Everglades region of Florida, and in Nyasaland on the manufacturing process of tea because tea fermentation is brought about by an enzyme that is a copper compound. Manganese also is locked up by organic matter in a similar manner. Soil reaction conditions have definite effects on nutrient availability. Of the standard trio N. P. K. potash is the least affected, serious diminution in availability becoming apparent only at pH values below 5.5. Nitrogen availability is optimal between pH 6.5 and 8.0. Phosphorus has a narrower range of maximum efficiency pH 6.5–7.5. Iron, so seldom considered when discussing problems of nutrition, but so vitally irreplaceable, declines steadily in availability at reaction values above pH 5.5.

CHAPTER VI

GREEN MANURING AND COMPOSTING

Soil Amelioration

From what has been said previously it is evident that organic matter in the soil is of the utmost agricultural importance. The colloidal properties of organic matter affect soil tilth and structure, regulate water relations and improve the base exchange capacity of soils. In addition, organic matter contributes nitrogen compounds and the many and varied mineral elements without which plants will not grow. In this chapter we shall deal in some detail with the ways in which organic matter can be returned to the soil.

The methods used to re-stock the soil with the carbon compounds and their associated nitrogen, upon which natural agencies and cultivation operations make a constant drain, are very diverse. In general they take four forms.

- (1) The marketable part of a crop may be only half or even a quarter of its total growth. The residue, not harvested, is available for turning in to the soil. The natural decay of all root systems is a constant source of valuable material. Root crops contribute appreciable quantities of green tops, and cereals of stubble straw. Tea which is

pruned at intervals provides a large bulk of leaf droppings from prunings.

- (2) Animals may be turned in to eat off *in situ* whole crops which have been reared for their nutriment. Even if not raised specially for this purpose, residues of crops (such as long straw) are trodden by sheep and returned in this way.
- (3) Where cereals are harvested with the straw, the latter is returned, after threshing, in the form of either compost or farmyard manure ; in both cases using the straw as litter for animals.
- (4) Crops may be grown specifically for turning in as green manure. In rotational cropping such crops would be catch crops. In plantation agriculture they are interplanted with the permanent crop. They may be either trees with a relatively long life lopped frequently to stimulate new and succulent growth, the loppings forming the green manure ; or they may be short term bush crops, lopped once or twice only and then uprooted and turned in.

Of the four methods of maintaining organic matter just enumerated, the last is most suited to plantation agriculture with perennial crops and well-distributed rainfall.

Nodule Organisms of Leguminous Plants

The most usual crops for use as green manures are those in the natural order Leguminosae. Their value had been evident in Roman times ; they were introduced into England from the continent during the Roman occupation

and their use was further systematised and extended after the Restoration. Only during the lifetime of our fathers was their special virtue scientifically explored and explained. Even now the picture is not complete. In the seedling stage of growth, about the time the first true leaves emerge, the minute root hairs are invaded by soil bacteria, *Rhizobium* species, which produce as appendages to the roots nodules of root tissue in which the bacteria multiply with great speed. The life cycle is complicated, and includes forms which are both static in the plant and mobile in the soil. From the plant the bacteria derive some nutrient and all their energy supply, but they are not dependent on the plant for nitrogen. They have the capacity for abstracting this from the soil atmosphere and of manufacturing it into complicated protein molecules of benefit both to themselves and the plant. Those species that produce pink nodules are more efficient than those forming white ones. The relationship between host and bacteria is known as symbiosis (=living together). The bacteria are dependent on the host for the full realisation of their life cycle, and the plant in the absence of abundant available nitrogen is dependent on the bacteria. If plants are fed with available nitrogen, then the nodules are decreased in number and their efficiency is also impaired.

Rhizobium bacteria have been classified empirically. Some bacteriologists are prepared to distinguish a number of definite species. Others content themselves with recognising a number of strains that are broadly distinguishable because they produce nodulation on certain groups of leguminous genera and not on others; or so it was believed when this classification was originally

adopted. For practical agricultural purposes this separation into typical strains prevalent in the nodules of lucerne, clover, pea, bean, lupin and cow pea respectively was useful in deciding whether a given crop would thrive in given circumstances. For example, land that would grow well-nodulating peas would also grow lentils and vetches, which were assigned to the same group, but not usually clover. Further research has shown that these cross-inoculation groups are not as sharply defined as was at first thought when relatively few of the almost ten thousand species in the Order had been examined. This wider investigation has disclosed that the largest group is the so-called cow-pea group and that the strain, originally restricted to a fairly small group of species, has very wide symbiotic relationships. This particular type of *Rhizobium* is found in some members of all three sub-orders into which the Leguminosae are divided, viz. *Papilionatae*, *Mimosoideae* and *Caesalpinoideae*, (which is not the case with some other strains). Still more striking is the fact that this group includes all the tropical species so far tested.

The cow-pea group is important for another reason. Its members and their symbiotes grow well on soils of relatively low fertility, and of low calcium status. In this they differ from the most commonly used temperate legumes belonging to the pea, clover and lucerne genera. These latter appear to have become distinctly specialised in their temperate habitats and at the same time more efficient in producing both nodules and fixed nitrogen.

The question of how the nitrogen fixed by symbiotic bacteria is made available to other crops depends upon

whether they are grown interplanted with the leguminous species or following it, but the process is not absolutely clear. The three possibilities are:

- (a) From the decaying nodules. (How much nitrogen is left in them when they are no longer actively synthesising nitrogen compounds is not known.)
- (b) From the plant as a whole when it is turned in as a green manure. In this case the free gift of fixed nitrogen is more or less completely returned to the soil.
- (c) From excretion by nodules into the soil during the growth of the leguminous plants.

From experiments which must necessarily be done under controlled conditions in pots, and which do not therefore entirely reproduce field conditions, it has been surmised that some of the fixed nitrogen is not retained by the host but is excreted into the soil and can therefore be used by non-leguminous species if such are growing at the same time along with the legumes. It has been shown that such associated crops have on occasions grown more vigorously than similar ones raised alone, and that the nitrogen present in them at harvest exceeds that which was added to the sand in which they were grown. The results of these experiments, made originally in Helsinki, were not confirmed when repeated in Wisconsin, England and S. Australia, although the manner in which they were conducted was the same. Eventually the divergence was clarified when the Wisconsin team of workers transferred their experiments to Helsinki. Agreement was then

obtained. The climates of the two places are markedly different more especially in temperatures and length of day. This caused radical differences in growth rates and in the physiology of the processes involved in nitrogen fixation and excretion. When nitrogen accumulates in the plant more rapidly than carbohydrate nitrogen is excreted. The climate and latitude of Helsinki give clouded skies and short days which favour accumulation of nitrogen rather than carbohydrate.

Even if excretion occurs there are various factors that may prevent the associated crop from benefitting. The relative growth-rate of the leguminous donor and the associated receiver must harmonise. Cereals are known to absorb most of the nitrogen in the first half of their growing period. Unless therefore the excretion from the legume takes place during this period, no benefit can accrue to the associated crop. A perennial acceptor might be expected to fare better. At present it is impossible to say whether this transference takes place under natural conditions at all, or under what range of conditions it may operate. On balance it seems safer to assume that the undoubted benefit conferred on the soil in respect of nitrogen status, and on crops growing either at the same time or subsequently, depends upon the disintegration of the tissues of the legume, which have been themselves enriched, either by natural death or by turning into the soil the loppings or the whole plant.

Benefits of Green Manuring

This brings us then to the general question of green manuring: that is, the usefulness of growing a crop, not

for harvesting and removal from the land but for enrichment of the soil itself. The example of a leguminous green manure is only a special case of a wider problem, special, because of the free gift of new soil nitrogen which it provides. Non-leguminous green manures are dependent entirely on ordinary soil resources for their supply of nitrogen. In what way then is the nitrogen status of the soil improved by their use? This question has been answered in principle in the previous chapter. Green manuring supplies the means by which the nitrogen compounds, broken down by microbial action into simple forms, easily lost, may be reintegrated by linkage with carbon. The method has a definite contribution to make in both the circumstances which ordinarily arise. The exigencies of a cropping rotation may leave soil under bare fallow for a time. A green manure crop garners for further use nitrogen which would otherwise be lost. Where the crop is a perennial one such as coffee, tea, rubber or coconuts, the main crop does not effectively cover the area during the whole period of its growth. Tea is a good example. For a considerable time after pruning, the bushes are devoid of leaf. The leaf removed by pruning is turned into the ground and quickly breaks down. A rapid-growing green manure crop planted at this time, or a permanent interplanted tree green manure which is in active growth uses and conserves nitrogen quickly released from the tea prunings, which would otherwise be lost in drainage water. In fact, notwithstanding all the admitted benefits of fixed nitrogen from leguminous crops, if these be used, the success of green manuring rests primarily on the skilful management of

the green manure whose carbon and nitrogen cycles are dovetailed into those of the main crop. Just what that skilful management entails it is now proper to enquire.

The Carbon/Nitrogen Balance

The crops or residues of crops that are available for return to the soil are very heterogeneous in form and composition. The older and therefore more mature they are the richer their tissues will be in carbon, and the poorer in nitrogen. Let us consider first the case of a residue of the maturer type, something of the nature of a straw from a cereal crop or a trash from a cane. As has been explained previously this type of residue provides an abundant energy supply for soil organisms which will rapidly multiply. They will require a supply of nitrogen too for which the material itself will prove inadequate. Its carbon/nitrogen ratio may be 50, and for self-sufficiency as regards both carbon and nitrogen a ratio no larger than 20 is necessary. There is an added complication due to the fact that the nitrogen compounds present will not be very easily decomposable and the organisms will satisfy their requirements from more available sources if they can. On the score then both of quantity and availability or assimilability, sooner rather than later, a state of nitrogen starvation confronts the attacking organisms. They will turn therefore to the simpler forms, ammonia and nitrate present in the soil, building them up into the intermediate but higher forms required for their own tissues, and thereby removing them from the range of ordinary cropping plants if any are present. In due course through cycles of growth and decay of the organisms themselves,

the excess carbon will be dissipated and the carbon/nitrogen ratio narrowed till equilibrium is reached and measurable quantities of nitrogen as well as carbon are released. So long as this process is not in competition with a growing crop, good rather than harm is done ; but if a growing crop is on the ground at the time, or before the stabilisation of ratio is attained, the result is acute nitrogen starvation for the crop. This starvation, though temporary, and involving no capital loss of nitrogen from the soil, may so hamper the crop at a time when ample nitrogen is a necessity that total crop failure may result.

At the other extreme there is the example of very young residues with a relatively high nitrogen content. Here the nitrogen supply will be in excess of microbial needs and the excess, broken down ultimately to nitrate, will be liable to loss in drainage if not absorbed by a growing crop. In brief then, materials of high carbon/nitrogen ratio are nitrogen-takers and are spoken of as having a positive nitrogen factor ; materials of low carbon/nitrogen ratio are nitrogen-givers and have a negative nitrogen factor. It is a simple matter chemically to distinguish between organic, i.e. protein nitrogen, and the simpler mineralised forms (which by common convention comprise ammonia and nitrate). The diagram in Fig. 4 gives the results of an actual experiment illustrating the factual basis of the argument just outlined.

Fig. 4 (a) is concerned with a grass (*Chrysopogon zeylanicus*) of fairly wide carbon/nitrogen ratio (27). The nitrogen content in the raw material is shown by the black column and is organic nitrogen. To it has been added

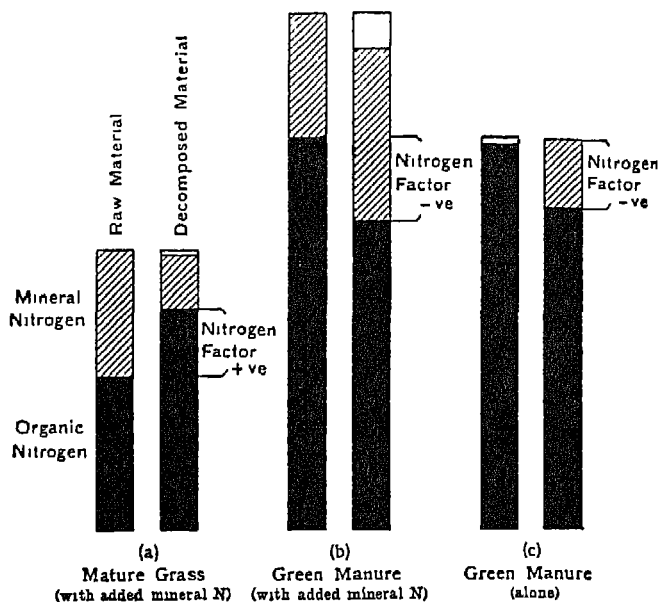


FIG. 4. Nitrogen Factors of different Plant Materials.

ammonium sulphate (mineral nitrogen) supplying nitrogen in the quantity shown by the shaded portion of the column. The whole was then allowed to rot down till it formed a typical compost which was then analysed. The first point of note is that the total nitrogen content before and after rotting is to all intents unchanged. The difference represented by the unshaded portion is accountable by sampling errors. The difference between the proportions of mineral and organic nitrogen is marked. A considerable quantity of mineral nitrogen has been converted into the organic form. That this has occurred is due to the wide carbon/nitrogen ratio of the original material. As

there was insufficient nitrogen to balance the carbon supply without using the added mineral type, recourse was had to this to build up microbial tissue, during which process it was converted into the organic form. The amount so converted is the positive nitrogen factor of this material.

In Fig. 4 (b) the circumstances are quite different. The green manure *Tephrosia Vogelii* has a much higher nitrogen content. Not only was the added mineral nitrogen not used in the decomposition process, but some of the organic nitrogen was itself converted into mineral nitrogen. In addition there appears to have been some loss of nitrogen. The addition of mineral nitrogen was in this case quite unnecessary and wasteful. The amount of organic nitrogen converted to mineral forms measures the *negative* nitrogen factor. Confirmation is given by Fig. 4 (c) which shows what happens when an identical amount of *Tephrosia* is allowed to rot without any additional mineral nitrogen. It has ample supplies and some to spare. Within experimental limits the negative nitrogen factor is identical with that of the foregoing experiment.

These results have a direct bearing on the degree of maturity at which green manures should be incorporated with the soil. Maximum crops coupled with a suitable carbon-nitrogen ratio are attained if cutting is done just prior to the flowering stage. The timing of the turning in of green manures is equally important even supposing that the carbon/nitrogen ratio is suitable. It may well happen that a catch crop may be ploughed in and release its surplus available nitrogen before the ground is in suitable condition for sowing the following main crop.

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At the Woburn Experimental Station vetches ploughed in during late autumn or early winter contributed no advantage to the succeeding crop on a light sandy soil. An equally unfortunate state of affairs arises when owing to minor drought the green manure has not decomposed sufficiently to release its nitrogen for the young main crop to benefit at the time of greatest usefulness.

In plantation agriculture with its perennial long-term crops these particular difficulties of management are minimised, and it is a fact of experience that green manuring has met with greater success in this type of agriculture, particularly in the tropics.

As an indication of the carbon and nitrogen status of diverse materials a selection of analytical data is given in Table II.

TABLE II

Composition of Various Materials with respect to Carbon and Nitrogen

<i>Material</i>	<i>Carbon per cent</i>	<i>Nitrogen per cent</i>	<i>Ratio Carbon/ Nitrogen</i>
STRAWS			
Wheat	40.9	.32	128
Paddy	34.6	.78	44
Manna grass (<i>Chrysopogon zeylanicus</i>)	45.3	1.68	27
GREEN MANURES			
Mustard	39.9	1.51	26
Tares	40.1	3.01	13
Tea foliage	43.6	2.52	17
<i>Tephrosia vogelii</i>	45.1	3.92	12
<i>Erythrina lithosperma</i>	45.4	4.06	11
<i>Gliricidia sepium</i>	40.5	2.74	15

GREEN MANURING AND COMPOSTING 83

Mexican Daisy (<i>Tithonia diversifolia</i>)	36.9	3.37	11
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ARTIFICIAL MANURES

Cottonseed meal	38.8	7.24	5
Castor meal	47.2	5.03	9
Groundnut cake	44.9	7.92	6
Blood meal	41.5	11.10	4

BULK MANURES

Farmyard manure	30.9	2.15	14
Compost	18.7	1.77	11

As has been indicated, not all crop residues are suitable for immediate incorporation in the soil. Such material needs to have its carbon/nitrogen ratio adjusted before being used on the land. Ordinary farmyard manure provides a way of using limited quantities of straw, but frequently there is a larger supply of material than can be used as litter by the number of animals available. In these circumstances composting offers a convenient and economical method of disposal. It is also suitable where mixed agriculture is not practised on a large scale.

Composting

There is a very diverse and voluminous literature on composting and the process cannot be dealt with here in detail because the essence of good composting is to make the best use possible of available material and conditions. Confining attention to general principles the following observations are important. The composting of materials of low carbon/nitrogen ratio is unnecessary and wasteful. The balance sheets of nitrogen in the aforementioned

experiments were highly satisfactory because they were done under controlled laboratory conditions. In practice there is always some loss, and with material rich in nitrogen this is likely to be severe. Provided that times and seasons can be satisfactorily adjusted, true green manures are better used as such to avoid this wastage, and to avoid also the extra cost which removing a crop for composting, and moving the finished product back again, must inevitably involve. This is particularly the case where the composted green crop is to be used on the same location as it is grown.

Sometimes in plantation agriculture the volume of the crop is too small to make its use profitable then and there ; or it may be culturally inconvenient to turn it in with a standing crop. In these circumstances it may be used with other materials, particularly those not suitable for direct green manuring, as a constituent in compost heaps. By so doing the green manure nitrogen, available by reason of a negative nitrogen factor, can be used to contribute to the nitrogen required for decomposition by the material having a positive nitrogen factor. In general, composting with mixed residues is likely to be superior to composting with homogeneous material because in so doing the nitrogen factor conditions are likely to be safeguarded. Moreover, mixed residues give a better structure to a heap and secure good aeration which is essential for the rapid and successful action of the micro-organisms.

Woody material except in small quantities as an aid to aeration is unsuitable for composting. The same is true of barks and coir fibre. Extraneous sources of nitrogen to satisfy the nitrogen factor are in many cases necessary.

Dung and urine are of the highest value if available. Dung has other advantages ; it provides a rich flora of organisms to help the decomposition, and it also helps to maintain an even distribution of moisture in the heap. Failing any cheap and ready source of nitrogen, artificial nitrogenous manure can be used. The most suitable is cyanamide, and the use of this particular material is covered by the Adco patents.

Where straws or dry grasses form the chief constituent, soaking the material prior to building the heap helps to procure uniformity in decomposition and evenness of texture in the final product. All materials are better for being chopped up into lengths of 3 or 4 inches, and a litter cutter provides a convenient way of doing this. Many materials have an outside surface which is highly impervious to water : if so, cut surfaces offer the only easy access to both water and micro-organisms.

In building heaps a total height of between two and four feet is best. Small shallow heaps lose water from their disproportionately large surface. If too high the weight of material compacts the lower layers and fosters anaerobic (=airless) conditions. Besides needing air and water the organisms are sensitive to reaction conditions and most materials require lime, plant or wood ashes to keep the heap in condition. When cyanamide is used for the Adco process no further addition is needed on this score.

Relative Value of Green Manures and Compost

Much discussion has taken place on the subject of whether composting is intrinsically superior to green manuring ; and whether composting has any further

effect than to adjust a possibly unsuitable carbon/nitrogen ratio and improve the physical condition of the material.

Claims in the affirmative stress two main points. In the first place they contend that compost is not really efficacious unless it contains some animal wastes. Good permanent agriculture has for centuries involved a cycle of processes alternating between crops and livestock, and therefore this claim is not one to be lightly dismissed. It may be that the chemical decomposition of animal wastes and excreta can contribute something which plant materials alone do not synthesise. To stipulate that this contribution is necessary raises the question of how the vegetative kingdom became established in the first place, and how generation after generation of plants and seed have been raised in water cultures; but in a moderate form the claim would rest on evidence to show that healthier, better and bigger crops were produced when animals have a place in the agricultural cycle than when they do not. The solution to this problem is not going to be easily or quickly provided, and when the claims are particularised by quoting instances in which spectacular results have been produced in a single season, either in respect of crop or disease incidence, they must be accepted with reserve by all to whom a critical approach commends itself.

All sorts of new substances have been found in plants recently with many interesting physiological properties. Of these the so-called "growth promoting" substances have received a great deal of both scientific and popular attention. Some such entity might be provided by animal remains, but proof of such a hypothesis is still to be sought.

A claim of a more important kind is that compost encourages a specialised type of fungus which lives a symbiotic life in association with the roots of many plants, particularly those which do not produce root hairs. This specialised root fungus (mycorrhiza) is postulated to have a profound effect on the nutritional physiology of the plant, so much so that without it, the plant never reaches full vigour.

Two types of mycorrhizal fungi occur: those whose hyphal filaments are mainly on the surface of the roots (ectotrophic), and contrariwise those where the fungus ramifies chiefly in the root tissues (endotrophic). In specific circumstances mycorrhizas of the former type may have a beneficial function. They may facilitate the transference of water and nutrient to the root from soils of meagre fertility. Whether this kind of action takes place when the mycorrhizas are endotrophic has not been established. The claim that without mycorrhizas plants do not attain full vigour is untenable. Critical investigations in connection with the Forestry Commission's development programme have shown that the nutritional benefits ascribable to mycorrhizal association can be provided by adequate manuring on conventional lines. The function of mycorrhizal symbiosis is by no means completely understood, and it remains a debatable point whether healthy vigorous growth of a plant is due to its associated mycorrhizal fungus, or whether the mycorrhizal partnership is the product of the good growth.

Returning to the question of the relative value of green manures and composts, there is one important distinction to record. Green manures grown for immediate use are likely to have a lower cellulose content than the mixed

materials from which the average compost heap is made, and their nitrogen content will normally be greater. The easily decomposable green manures have little effect on the formation of soil crumbs. On the other hand the tougher material, higher in cellulose content and lower in nitrogen will improve humus reserves. The various kinds of vegetable tissues that are returned to the soil or are made into compost have a whole gamut of carbon-nitrogen ratios. On the high side are straws from cereals, trash from sugar cane and pulp from sisal. In the lower range are prunings from tea and loppings from green manures and shade trees. To a varying extent these materials will build up humus or release stored nitrogen in an available form. They will not efficiently do both at the same time.

The remains of a healthy well-grown plant contain (by whatever processes we need not enquire) those elements of nutrition which are indispensable to plant growth. By returning them to the soil, one is safeguarding their retention in the best and simplest possible way. It is now known that for lack of the merest traces of such elements as copper, zinc, boron and molybdenum, whole tracts of land can become unproductive or the animals they maintain suffer from disease. The use of plant and animal residues as manure must necessarily conserve these valuable trace elements.

Until further work clarifies the issues it is safest to look upon green manuring and composting as two alternative or complementary methods of achieving the same object, the maintenance of soil fertility by the conservation of everything that contributes both to good nutritional and physical condition in soil.

CHAPTER VII

CULTIVATION

THE common answer to the common question "Why is soil cultivated?" (thereby meaning physically disturbed by cultivation instruments) is "In order to aerate it." Simple as the answer may sound, it is highly deceptive. One might equally say "Why do we eat?" and answer "To live." In both cases the question and answer skip from start to finish and leave out all the middle.

Cultivation in Relation to Soil Aeration

It may be objected that obviously by breaking up the land, air is let into it. Walking across a newly cultivated field one sinks into the surface layer. That in itself demonstrates that considerable air spaces have been made in the disturbed soil. But before accepting this as an adequate demonstration of aeration let us ask a few questions and record a few observations.

What is the average depth of cultivation in a field prepared for barley, in an orchard, or in a plantation of coffee, tea or rubber? Under these diverse conditions of crop the answer would be between three and twelve inches. Subsoil ploughing, a very occasional operation, will disturb something like eighteen inches. Now contrast these dimensions with the depth to which the feeding roots of the respective crops penetrate. Figures from root surveys of barley show depths of 4-5 ft., for coffee 6-9 ft.

and for tea even greater depths. Spacing, soil type and other cultural conditions exert a marked effect, but the point is that roots are found in profusion at depths much greater than the depths of cultivation.

When a plant is transplanted, the soil around the roots is purposely compacted even though it has recently been cultivated. For some crops such as turnips the land is rolled after the sowing of the seed. Evidently the large air spaces produced by cultivation are not what is primarily required.

In soils not recently cultivated the amount of pore space, filled with air or water, averages about fifty per cent of the total volume. Permanent grassland or forest never gets cultivation in the sense here considered. Whatever the aeration channels are that effectively keep the soil in condition and the vegetation in healthy growth, they are of such dimensions as decaying rootlets and worms can make. The paddy crop lives satisfactorily for a large part of its life-cycle in soil covered by standing though not stagnant water.

Soil Aeration and Water Movement

A truer perspective can be had by considering cultivation not from the immediate viewpoint of aeration and air movement but in relation to water movement. Broadly considered, a soil will be well aerated if water movement through it is free. Percolating water displaces air from the interstices of the soil. Such air will be relatively poor in oxygen and high in carbon dioxide, as compared with that from atmospheric sources. The entering water contains dissolved air and this air is richer in oxygen than normal

air. By this mechanism air, including oxygen which is what is really required, is distributed throughout the range of root action, and far beyond the limits of cultivation.

When land is taken into cultivation and stripped of its vegetative covering, the speed at which forces tend to destroy crumb structure is increased. The water-stability of the soil crumbs varies greatly according to soil type and treatment, and in time, sometimes quite rapidly, water action, rapid drying and the increased oxidation which exposure offers, may denature a thoroughly crumbly and satisfactory soil. Everyone who has lived in contact with farm and plantation operations is familiar with soils which either cake and crack badly, or "run", forming a structureless cap which can and does play havoc with the rootlets of young seedling plants. Not infrequently, material from the surface is washed down the crevices and forms a cementing layer at a lower depth which eventually leads to the formation of an impervious layer or pan. This is particularly the case where compounds are dissolved from the surface soil, and, because of a change in reaction, or other conditions, are reprecipitated at a greater depth.

All such phenomena are natural occurrences, but, in addition, farm and plantation practice may accelerate the destruction of tilth. The treading of land by sheep when eating off a root crop is usually of distinct benefit to the soil and subsequent crops. It may happen that because of weather conditions the treading will lead temporarily to a very deflocculated soil state. In tea plantations there is a constant traffic up and down the rows for purposes of plucking and weeding. This compacts the first few inches

of a soil quite considerably and it is a simple matter, with suitable apparatus to determine that compactness by measuring the force necessary to drive a steel probe through the successive layers of soil. Fig. 5 depicts the resistance curve for a typical tea field.

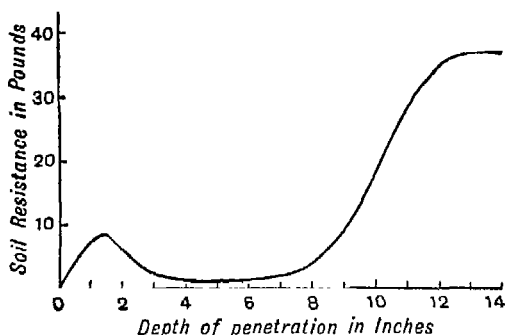


FIG. 5. Soil Resistance to penetration of Steel Probe.

The general effect of all these processes is to diminish the ease of percolation of water. What that means in terms of soil erosion will be dealt with in the next chapter. At present attention will be confined to that aspect which was mentioned earlier, the slowing down of the interchange of what we may call exhausted air and fresh supplies. The first aim of cultivation then is to break up these clods, caps and pans. Coupled with this operation is that of incorporating in the soil fermentable materials, stubbles, bulk manures, green manures and leaf-fall which by their colloidal nature will build up again the crumb structure that has been destroyed. As the materials rot they shrink in volume and provide interstices which are of much more importance than the original air pockets caused by the lumpiness of a newly cultivated field.

Contrasts between Annual and Perennial Crops

When cultivation is under discussion it is necessary to distinguish between that carried out in preparation for *annual* farm crops and that needed for the maintenance of larger and *perennial* plants of the plantation type. The most conspicuous cultivation on farmland is preparation of a seed bed. The subsequent development of an annual crop is tremendously influenced by its growth and establishment in the first few weeks after sowing. Within limits, the yield per acre is a function of the number of plants per acre, so that good germination is essential. Some crops are especially sensitive to soil conditions in these early stages. Barley, turnips, mangolds, sugar beet sown on rough land, not broken down to a good tilth, are predestined to relative failure. In consequence, for annual crops cultivation is carried out with a refinement unnecessary for larger and more permanent crops. Even for annual crops the comminution of the soil must not be carried to excess. Power-driven rotary cultivators disturb the soil very thoroughly but the cropping results following this type of cultivation are not found to be superior to those given by the more standard farm operations, and in actual trials were sometimes inferior.

Turning aside from this question of the preparation of a seed bed there remains that of what is to be regarded as sufficient during the later life of the crop in the case of both annual and perennial plantation crops? How often is it necessary in the interests of water percolation to hoe or fork land under a standing crop, having regard to the undoubted damage that such an operation will do to the

shallower parts of the root system? In any crop, cultivation becomes increasingly difficult as the plants mature and increase in size.

The results of experiments on both annual and perennial crops give perfectly concordant results. They are that intensive cultivation depresses crop yield, and by intensive is meant cultivation in excess of what is required to control weeds. To the function of controlling water absorption by cultivation must be added that of destruction and control of weeds. This is an exceedingly important function of the process, but the soil stirring that it involves is only incidental.

Mulches

The pulverisation of the surface soil has often been advocated as a means of conserving the water supplies of the soil by breaking capillary channels and prevention of evaporation at the surface. This hypothesis has been dealt with previously and shown to be valid only for soils with a water-table within a few feet of the surface, or whose textural constitution is very specialised. These conditions are rare, and as part of a general argument for frequent and severe cultivation the capillary mulch theory is totally unsound. Soil will become self-mulched by the drying out of the surface layer till the loss of water through that layer is exceedingly small. That does not alter the fact that the layer in question may contain the bulk of the feeding roots of the soil and that self-mulching may do little or nothing but harm to the growing crop. Any procedure which will reduce the temperature of the soil and minimise air movement at the surface will be far more

valuable than the maintenance of a fine soil mulch. Some crops provide ample shade and thickness of stand for this purpose, but spaced crops have periods when the bulk of the soil surface surrounding them is bare. In some circumstances a green manure crop would answer the purpose, but only if it were drawing its moisture from layers much deeper than that of the main crop. That is one reason why shade trees are more suitable than ground species in dry weather. The water they absorb may be taken at the expense of the crop eventually, but they keep the ground cool and minimise transpiration by the more leafy main crop, and act as wind breaks.

Good results can be had from mulching with the sort of plant residues that are put into a compost heap. The ordinary green manure loppings are not a very important contribution because their volume is small when dry, and they are quickly dispersed by decomposition. Several inches of straw or long grass on the other hand is very effective. In addition to reducing evaporation a mulch will improve the acceptance of rainfall provided that it is not too thick. The maximum benefit was derived from mulching coffee in Kenya when the mulches were prepared well in advance of the dry weather. The material must be kept on the ground until rain in quantity arrives and it is a good plan to let it remain *in situ* for several months, until it shows signs of decay. Then it can without difficulty be turned in. Green manure loppings or artificial fertilisers turned in at the same time in the normal routine of plantation practice will amply safeguard the necessities of a still remaining positive nitrogen factor. The establishment of young plantation crops is

often made very difficult during the early years by more or less prolonged periods of dry weather. The use of mulches has been shown to help considerably by reducing casualties and promoting more vigorous growth generally.

CHAPTER VIII

SOIL EROSION AND DRAINAGE

Tropical Luxuriance and Soil Fertility

The luxuriance which is a feature of the vegetation of large tracts of tropical and sub-tropical countries suggests that the soils of these areas are rich, and capable of bearing crops for an almost indefinite time. This view is commonly held but is for the most part entirely illusory. Closer consideration shows why this is so. Conditions of temperature and rainfall are such that rapid growth is possible, given other suitable circumstances, and this rankness lends colour to the superficial but uninstructed view just mentioned.

Many of the soil formations in tropical areas are of great antiquity, and in the process of weathering, high rainfall has removed the greater part of the valuable nutritive elements from the surface soil and has leached them beyond the range of arable crops. It is true that these same factors of rainfall and temperature speed up weathering processes so that, relative to what occurs in temperate climates, new soil is built more quickly, but the forces of soil destruction are so much more potent, that this replacement is of no immediate practical value to the agriculturist. Particularly in respect of nitrogen and carbon compounds the quicker decomposition only accentuates the process of loss.

To argue from the appearance of jungle growing on a soil to the potentialities for cropping on that soil is to rely on what is largely a false comparison. The economy of forest is one of the strictest in nature. When left undisturbed the cycle of growth and decay proceeds under optimal conditions and the balance of that economy tends towards building up of fertility rather than to its depletion.

All agriculture is artificial and involves the breaking away from natural conditions. This is inevitable because, in the first place, crops are carried away from the growing place, and secondly, much more rapid growth is purposely planned, otherwise crops would not be an economic proposition. To achieve this the steady turnover of capital in the form of nutrients must be speeded up, and chances of loss are increased in like proportion. Burning for clearing destroys in a matter of hours what nature has accumulated over centuries, and the commencement of cultivation accelerates soil destructive forces at a time when there is no vegetation to respond to the increase in release of nutrients.

Whilst accepting that a destructive phase is unavoidable it is important that the operations of felling, burning and cultivation should be carefully regulated otherwise within a matter of a few seasons after felling jungle the rich litter that would normally be broken down on the spot to form humus may be completely and uselessly dissipated. In the absence of efficient methods of conservation even the residual ashes can be readily lost. There is then left a soil which is potentially less fertile than the average of temperate zone soils. The wider aspects of the fertility of tropical soils are considered in the following chapter.

Here we are concerned with the loss of soil itself, brought about by the accelerated erosion that is the natural consequence of exposing the soil to the elements under unfavourable topographical conditions.

Where, as in temperate countries, land has been under cultivation for centuries, it is mere fantasy to suppose that crops are still exploiting the unfathomable reserves of past ages. Without exception, high fertility in these cases is the result of careful management which not only conserves the initial soil capital but maintains or increases it. Good arable land is in the strict sense of the word man-made. The disasters of the American dust bowl regions and the difficulties in Australia's marginal lands are sufficient evidence of how soon fertility can be ruined if control measures are not given first place in importance.

Varied Aspects of Soil Erosion

The necessity of conserving and improving tropical soil fertility is even greater than for temperate soils because in addition to loss of the characteristics of fertility, high rainfall and often mountainous contours promote loss of the soil itself. Loss of crop from erosion is more serious than from disease. When disease is checked, a normal healthy plant can be raised, but from soil erosion permanent damage results.

The implications of soil erosion are very widespread. The tale of destruction is only started when an account has been given of what happens to land that loses soil. What is carried away will impair the fertility of the eroded area. It cannot contrariwise be said that this eroded soil

will be deposited elsewhere as a rich deposit. If the process was one of robbing Peter to pay Paul it would still be deplorable, but unfortunately the deposited soil is without exception itself infertile and only becomes bettered by constant labour and attention. Sometimes it never does reach any satisfactory level of fertility. The reason for this paradox will be explained later.

Roads and railways are frequently destroyed by floods caused by the run-off water made doubly destructive by carrying soil and rock fragments that increase its momentum; rivers are rendered unnavigable and reservoirs made inadequate by silting up. Other fertile acres, as has been mentioned, are overlaid by infertile silt, and drought conditions can be spread over a large area because run-off water has precipitately left a water-shed instead of soaking gradually through the surface to the sub-soil, maintaining there extensive regions of soil at a good field-capacity with a water-table at reasonable levels, and reappearing in a desirable guise in springs and clear rivers over a considerable space of time. These are but a few of the types of damage that soil erosion can and does produce. We are mainly concerned with localised agricultural damage, but the more extensive ruin should never be forgotten.

Soil Structure and Erosion

The fundamental cause of soil erosion and subsequent damage is loss of structure by the soil. Some soils are more erodible than others: that is because they are more prone to lose their crumb structure. Once crumb structure is destroyed the percolation of water is impeded, the surface layer becomes saturated, and loosened particles

are bathed, lubricated and borne away by water which has to flow over the surface instead of seeping through to lower depths and normal outlets. Investigations on the properties of soils that are conducive to erosion have not been carried out on a sufficiently wide scale in sufficient places to make it possible to classify soils in order of merit as erosion resisting, but some broad facts are known about the relationship between erodibility and physico-chemical properties. Soils that are well provided with basic minerals and which swell and shrink markedly on wetting and drying are particularly liable to erosion. So are those whose finer particles (the clay of mechanical analysis) have a high proportion of silica to alumina in their chemical composition. In effect this means that temperate soils are more susceptible to erosion than tropical ones. What saves temperate soils from destruction is the moderate and well-distributed rainfall (though in dry regions erosion by wind may work incalculable damage too). Placed in a region of tropical rain, the resulting erosion would be more devastating than what is actually encountered there. Tropical erosion is serious enough as it is : it is a fortunate provision of nature that arranges that the type of weathering that occurs in regions of high temperature and rainfall should produce a soil that is *relatively* resistant to erosion. Quite the worst erosion ever seen by the writer occurred on land in South Australia where the average rainfall did not exceed fifteen inches per annum. A fall of two inches in the course of a day on soil whose weathering processes were not tropical, carved out gullies, breached roads and changed the topography of thousands of acres of gently rolling country. In Ceylon with its mountainous hill-

sides such a rainfall is more than frequent and leaves the countryside very much as it found it.

The literature of soil erosion is extensive and only a brief survey of soil erosion can be given in a single chapter. Rather than try to epitomise every aspect of soil erosion and run-off, it will be more useful to trace the implications of the one fundamental point about soil structure and percolation in some detail.

Much has been made in past times of the effect of heavy beating rain in destroying the crumb structure of arable surface soil. The importance of this particular factor is greater in temperate soils than in many tropical ones. When soil crumbs are repeatedly wetted and dried they tend to slake and break down into smaller aggregates. This is noticeable in temperate soils and results in the formation of a close-packed continuous cap on the surface. In temperate agriculture this is harmful because it damages fine roots and impedes their penetration. It also puddles the soil and prevents percolation. In situations where erosion is conditioned by slope, such a barrier to percolation would rapidly cause saturation and run-off. Moreover, because the particles in a slaked soil are small, they would be the more easily borne away in surface run-off. The argument is allowable, but notice must be taken of the actual amount of slaking that occurs. The processes of tropical weathering which generate the widely distributed kaolinoid soils produce a residual soil that is relatively water-stable, i.e. whose crumbs are not so easily dispersed. This can be demonstrated by sieving a soil in water. If a dry soil is sieved through a mesh of 3 mm. and then through one of 2 mm., the particles left on the second sieve will have

dimensions between the two limits. If the soil on the 2 mm. sieve is allowed to slake in water for twenty-four hours and then simply moved up and down in a bucket of water there will be a minimum of abrasion of the particles by the mesh of the sieve, much less than with the usual rotatory motion of dry sieving. If slaking has disrupted the crumbs there will be a loss of soil through the mesh. In the course of about thirty such motions it will be noticed that further breakdown has virtually ceased. The particles move about in the tide of water and return to the surface of the sieve without the water becoming cloudy. A much higher proportion of crumbs (measured by their dry weight) will be found to remain on the sieve in the case of a typical tropical soil than for a soil of temperate origin. The results of an experiment of a different type may be quoted. Several plots of soil were cultivated with a digging fork and half of them were left exposed to the weather for 17 months, during which time they experienced two wet seasons and 150 inches of rain. The other half were covered with a mulch of long grass 3 inches thick. At the end of the experimental period, the mulch was removed. The protected plots were not visually superior to the unprotected in surface appearance. There was no cap or crust. By means of a specially designed steel probe, the resistance of the soil to the penetration of the probe was measured to the depth of forking. The results showed that there had been no compacting of the soil on the unprotected plots as a result of the beating or slaking action of the rain. All the plots were isolated against treading during the course of the trial.

For these reasons, although no soil has an absolutely

water-stable crumb structure, it is evident that typical soils of tropical and temperate origin behave quite differently under conditions of water saturation.

On steep slopes with heavy rain and severe run-off, soil crumbs are more readily broken down so that drains, water courses, streams and rivers rapidly become loaded with particles of various sizes. Eventually as water movement becomes sluggish these particles are deposited, the heavier ones first. The first to sink are unweathered grains of sand or rock which produce a deposit which in the nature of things is infertile. Later on particle size diminishes to colloidal dimensions and the deposit forms a sheet of silt or mud. This material is devoid of crumb structure and there is much less variability in particle size than in an ordinary fertile soil. Consequently such deposits are very retentive of water and are apt to be waterlogged, and even if this state of affairs is not very noticeable they are difficult to cultivate. Until such soils are worked sufficiently to give them a crumb structure they too are infertile. It is a fairly universal observation that soils which have been formed thus are less rich in organic matter and humus than those from which they are derived, and the incorporation of organic matter is a prime necessity in restoring their fertility, both as regards crumb structure and reserves of valuable nitrogen. This explains the remark made earlier regarding the damage done both on the original site of erosion and on the other site where the deposit is accumulated. The original soil is impaired in structure and the new soil has no crumb structure at all.

Prevention of Erosion by Ground Cover

Erosion and run-off may start in a small way and rapidly mount to alarming dimensions. Although a slaked cap is not readily formed in tropical soils the partial percolation of silt-laden run-off through a fertile soil clogs the pore spaces. The fine particles are filtered out and form a layer, not necessarily of any depth, which imposes a barrier on normal percolation. No matter how adequately channelled the lower layers of soil may be, the percolation through them is decided by the impervious layer above. The top inch or two of soil thus rapidly becomes saturated and liable to run-off. The process is continuous and the surface is carried away a little at a time, always leaving behind the "filter" to impede water percolation. It is probable that this phenomenon is the most serious cause of erosion with which agriculturists have to contend. The most efficient preventative is a layer of incompletely decomposed "litter" on the surface. The large absorption capacity immobilises the rainfall and checks run-off; but even when fully saturated it continues its beneficial work, for it prevents the washing down of the fine particles into the soil proper, and thus also prevents the formation of the impervious layer previously mentioned. In its most complete form it is seen in forest, and it is easy to realise what an incalculably potent preventative is destroyed when forest litter is dispersed at the time of exploiting forest land for agricultural purposes. The fact that in few agricultural systems, except those devoted to perennial species such as cacao, tea and rubber, can the litter be maintained is a reminder of how devastating man's

agricultural operations frequently are as regards soil conservation.

The percolation filter effect is just as serious on grass land as on arable land if the former is misused. The maintenance of too many stock on a grassland area leads to overgrazing and damage to the recuperative power of the species that form the sward. Properly treated there is no finer protection from erosion than grass and allied herbaceous species. But overgrazing results in the development of small patches of bare ground. On these the surface soil is finely pulverised by the treading animals. When rain falls, percolation is diminished and hence the water reserves are lessened, imperceptibly at first. Less water reserve means less growth during relatively dry weather and this accentuates the shortage of fodder and increases the overgrazing ; and so the vicious cycle goes on with accelerated intensity. From being a purely local phenomenon, it may, because of a falling water-table, become regional and attain incalculable dimensions.

Where mixed farming is practised, modern methods of maintaining soil structure are centred round crop rotation, particularly the growth of grasses and clovers for several years in the cropping series. In addition to preserving crumb structure such " leys " conserve nitrogen by linking it with carbon as was pointed out in the chapter on green manuring.

With perennial crops this method is not possible but ground-cover crops provide the most suitable alternative. These may be either artificially planted species, usually leguminous, or carefully controlled natural vegetation. The rubber plantation is ideal for this type of conserva-

tion. It is necessary to choose the species that are allowed to grow with some care, and what suits some conditions will be unsuitable in others, but a good deal of progress has been made in this so-called "forestry" system of rubber cultivation. In tea which is artificially kept at a low height by plucking, such methods are impracticable because the cover soon impedes the growth and harvesting of the crop by growing through the bushes. Many leguminous species are also undesirable because they climb over the bushes. Low-growing herbaceous weeds have been spasmodically tried, but this method is not yet out of the experimental stage. The loss of crop from competition is not so severe as might be thought and varies from about two to eight per cent. The cost of maintaining such a controlled cover is high in many places. In Assam a reasonable compromise has been reached by hoeing, but the terrain is admirably suited there for hoeing operations, and in any case the flatness of much of the land is not conducive to severe erosion. Cacao provides its own heavy litter of leaf-fall as a very substantial anti-erosion device.

Contour Planting, Terracing and Draining

In circumstances where a permanent cover cannot be maintained some second line defence in the form of specialised planting, cultivation and drainage is required. Contour terracing and contour planting are the most successful. If the latter is adopted, the distance apart of the plants must be such that a continuous hedge is produced. For instance, tea is frequently planted in rows with the bushes $3\frac{1}{2}$ feet apart. Contour rows with this



style of planting offer an inadequate barrier to run-off and soil wash. At $1\frac{1}{2}$ or 2 feet between bushes in the row, contour planting makes a real contribution ; and gradually the land forms itself into contour terraces.

Any form of terracing is advantageous, and in stony land rough masonry walls can sometimes be constructed, their main disadvantage again being cost. In tropical lands liable to sudden deluges of rain or prolonged periods of rainfall of a more moderate type, some system of drainage is essential. Pipe drains, as used on farms in temperate zones, are impossible since the structure, size and range of roots would quickly break or clog them, and their dimensions are too small to fulfil their function properly. Open drains are the rule, but according to their design they may counter or aid the destruction by erosion. The open unobstructed drain with a rapid fall (1 in 30) in herringbone pattern should by now be inadmissible. It leads to scouring and gullies and ensures that eroded soil is permanently lost. In its place gently sloping drains (1 in 80 or 100) should be used, blocked at intervals of 15 feet or so by bunds 2 feet long rising to within 3 or 4 inches of the ground level. The sections thus form a continuous series of silt pits into which run-off is spilled, and where, in all but extreme cases, the surplus rain can seep through the soil leaving behind it the eroded soil. If rainfall is continuously severe the water can spill over and be carried away, for the drain then becomes an open one. This safety valve is not needed on every occasion, and 3 or 4 inches of spill are sufficient for any emergency. In any event the bunds tend to impede the run-off and decrease its scouring effect.

There are other considerations besides soil erosion to recommend this system. In times of ill-distributed rainfall bunded drains conserve moisture. A soil baked hard by drought is bound at first to be relatively impenetrable owing to airlocks in the soil pores and channels. A heavy but short-lived storm will bring about severe run-off, and, if not arrested, only a fraction of the precipitation will be available to the crop. Within a few hours or days at the most the soil will be once again arid. By catching this run-off in bunded drains it is stored and seeps through the ground and is available for keeping the subsoil reaches of the soil moist and productive.

The style of obstruction in open drains can be varied in many ways. Instead of bunds the floor of the drain can be cut into a saw edge pattern such that the slope of the teeth runs counter to the general fall of the drain. Such a pattern has been called "reverse slope". The spill in this case is lower than the field level to allow for emergencies. This pattern is only half as effective in holding up run-off as the bunded type and its chief claim to consideration is that existing unbunded drains can easily be converted to the "reverse slope" pattern.

The siting of drains should be as nearly on the contour as circumstances allow. Their distance apart depends on the slope of the land and its texture. Inadequately drained land frequently shows a marked variation in vigour of the crop, the growth diminishing as the distance from the drain increases. Shape of drain is also dependent on the texture of the soil. A tenacious soil will need deeper drains, and a V cross-section is desirable, but for a stiff loam eighteen inches usually suffices and a rectangular

cross-section is suitable. These are matters which can only be decided by experience of the varying soils and localities encountered.

CHAPTER IX

THE MAINTENANCE OF SOIL FERTILITY

IN this account of the elements of tropical soil science we have, so far, considered the fundamental properties of soil, and have related them to certain aspects of soil management inherent in the exploitation of soil for agricultural purposes. Throughout these discussions the problem of soil fertility and its maintenance has been implicit. It is now appropriate to put the various aspects of this question into perspective.

Contrasts: Temperate and Tropical

In the temperate lands of western civilisation climate, technology and socio-political conditions have combined so to influence agricultural methods that broadly speaking the fertility of farm land is notably greater than it was before the second agrarian revolution gathered its great momentum in the eighteenth century.

Although intensive tropical agriculture has been carried on in selected places for an equivalent period the same cannot be said of fertility in the tropics, and for very cogent reasons. The environment is harsher and consequently even undisturbed soils are of poorer fertility. The socio-political conditions have also been adverse. Technology and affluence combined strongly favour good agricultural practice. These helpful circumstances have been absent in the tropics except in the best plantation

agriculture. The crucial question is whether even under the best conditions tropical fertility can be conserved, not to say advanced?

The simple term soil fertility embraces a very complex reality. To regard it as a single factor in an agricultural situation is convenient, but tends to over-simplify the problem. Fertility cannot be measured in terms of nutrient content only though adequate nutrient capital is important. Nor does the presence of abundant crops necessarily betoken a highly fertile soil if, for instance, fertilisers have been liberally used. At best heavy crops show that the soil has characteristics conducive to good fertility other than abundant supplies of nutrient. A soil's real fertility is shown when fertiliser supplements are withdrawn. Furthermore soils of apparently equal productivity vary considerably in their capacity to retain their fertility in adverse circumstances.

The Fertility Equilibrium

At a given time in a given place the fertility of the soil is determined by the equilibrium between the degenerative and restorative activities coexisting in the environment. Erosion, leaching, destructive microbiological processes and crop removal bring about loss of fertility. Physical changes brought about by soil disturbance are on balance detrimental. Nutrients are in a continual state of flux in the layers of soil exploited by vegetation. They are slowly released by weathering; immobilised in the debris of plant remains; lifted from subsoils to surface and deposited as litter. A whole series of biochemical and physico-chemical reactions takes place which affect

their stability. Carbon and nitrogen extracted from the atmosphere by living organisms represent real gains in the components of a fertile soil, set against the inevitable losses. In addition there are substances from outside the immediate environment brought in either by natural agencies, (e.g. the deposition of flood silt and erosion debris) or by man in the form of manures and fertilisers. From this incomplete statement of recurring events it is plain that soil fertility is intimately linked with the entire ecological situation comprising soil, vegetation, climate and the interference of man. The skilled husbandman can use the complex of circumstances so as to increase soil fertility if he is working in temperate climates. There are records of English farm lands being under arable cultivation continuously for more than three hundred years. Their present superior fertility is obviously not the residue of virgin fertility: it is man-made. Tropical fertility also must be man-made or controlled, for the comfortable assumption that jungle soils are immeasurably rich is fallacious.

The stability of the fertility equilibrium is precarious, destructive forces being generally the more potent. Under certain conditions it can be relatively steady. The closed economy of undisturbed forest is probably the most obvious example of a steady state. In an equable climate a well-conceived agricultural system, or any other ecological condition, not subject to drastic change, will establish its own equilibrium point. Even when the system is obviously inadequate or wasteful the loss in fertility is not total. A time arrives when a low but immutable residue of fertility persists in despite of everything. The long

cultivated lands of India, subjected to a primitive subsistence type of agriculture, have revealed this asymptotic level when large numbers of soil samples from diverse cultural conditions have been analysed and their results collated. The criteria on which these conclusions are based are the nitrogen and organic matter content which are in practice particularly susceptible to variation.

The Ecological Factor in Fertility Control

No convincing case has ever been made against the proposition that soil fertility is vitally linked with the maintenance of a steady state of organic matter, and soil investigations confirm that this is so. Mention has been made in previous sections of four specific ways in which organic matter exerts a regulating function namely, by base exchange phenomena, water retention, nitrogen conservation and in phasing the availability of nutrients particularly of nitrogen, phosphorus and minor elements. The over-riding factors that determine at what level the steady state of organic matter persists are rainfall and temperature. Bad husbandry can accelerate deterioration but the upper and lower levels of the organic matter equilibrium are dependent on climate. To build up a good reserve of organic matter in a soil is an entirely commendable activity but it must be realised that in a particular environment, i.e. in a definable ecological zone, intensive efforts to increase permanently the organic matter will be fruitless once the soil humus has reached its natural maximum in the said environment. It follows that it is much easier to rehabilitate land of moderate fertility than to augment the fertility of good land.

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Traditional recognition of the importance of the ecological factor in regulating the conservation and circulation of nutrients is evidenced by the schemes of shifting cultivation in primitive types of tropical agriculture. The generally adapted sequence: clearing—burning—cropping—forest fallowing, have in fact ensured a measure of stable fertility in Africa and Asia that has been demonstrably lacking when traditional methods have been replaced by continuous cropping with a view to rearing cash crops in an exchange economy, or because of land hunger.

Recent investigation of representative systems of shifting cultivation has produced data which, if confirmed, will upset some traditional views about fertility conservation. It is suggested that of the two sources of fixed atmospheric nitrogen, leguminous symbiosis and autotrophic bacteria, the latter are of greater importance than has heretofore been realised, because so many of the rhizobium strains found in tropical legumes are of low efficiency. In addition it has been concluded from the aforesaid investigation that the standard of fertility maintained by savanna grass is not so high as that from forest fallow. In this respect therefore tropical experience tends to discount the rating given to grassland as a preserver and improver of fertility in temperate agriculture. In the tropics grass land used for grazing is subjected to burning in due season.

The system of shifting cultivation has usually been regarded as wasteful in the extreme. In the first place the burning destroys organic litter, but it does not apparently consume the soil humus. About ten per cent of the litter is capitalised. The forest fallow which restores and

stabilises fertility needs a period on the average three times as long as the cropping period and therefore drastically reduces cultivated acreages.

Fertility in Relation to Intensive Cultivation

The considerations discussed in this chapter leave the agriculturist on the horns of a dilemma. On the one hand the climatic conditions in which the soils have been formed, and those in which agriculture is presently carried out, are so strikingly inferior to those obtaining in temperate regions when judged as conservers of fertility that it is not surprising that tropical agriculture has not attained the stability of temperate farming. On the other hand, the traditional methods of fertility maintenance are anachronistic in a world of expanding populations needing and demanding living standards better than that of mere subsistence. What systems can be evolved to replace archaic practices and to adapt modern methods, imported from a different environment, so that high steady states of fertility can be maintained in the tropics? The answer to such a question lies more in the province of the agronomist than of the soil specialist but wherever and by whosoever the attempt is made the following factors will need consideration.

(1) The long-term conservation of fertility is indissolubly linked with the preservation of organic matter.

(2) The organic matter must have a reasonably high content of cellulose and some lignified tissue. Green manures offer a useful means of stopping nitrogen losses by drainage, but they contribute little to a stable nitrogen reserve.

(3) Crop rotation (as in temperate lands) provides the best method of preserving fertility in annually phased agriculture though it is not likely to be so potent an influence in tropical regions. High savanna grasses are probably the most promising basis for a ley though some, (e.g. the members of the order *Andropogoneae*) are disappointing.

(4) In monocultures no such rotation is possible. Tree crops such as tea, coffee, cocoa and rubber by their natural leaf fall and, in some instances, their periodic pruning have a greater conservational potential than annuals. Their contribution to organic litter can be augmented by interplanting with tree species. This is a commonly criticised practice that needs much more comprehensive investigation before it is discarded on the grounds that on a short term basis it may affect crops adversely. There are indications that tea soils ecologically conditioned in this way for fifty years have higher carbon and nitrogen values than before the crop was planted. Moreover when disturbances either economic or beligerent curtailed fertiliser applications the diminution of yield was less severe than with a strict monoculture. Sugar and sisal have their own trash and residues that are potent preserves of fertility.

In conclusion there is no inherent antithesis between the advocates of more organic matter and more fertilisers. Countless experiments have shown on the one hand, that the skillful use of fertilisers can be made to contribute to the organic reserves of the soil, and on the other that organic matter increases the responses to be gained from fertiliser applications.

CHAPTER X

FERTILISERS AND THEIR USE

The Origins of Artificial Manuring

The practice of manuring reaches back into times of which we have no reliable records. The use of animal excreta for centuries formed the basis of the manurial side of husbandry. Even what is called artificial manuring is not as new-fangled as might be thought. The diarist John Evelyn speaks of the use of blood, hair, feathers, fish and malt residues as being used for crop improvement in the middle of the seventeenth century and other writers at the same time refer to rags, wool combings, bones of animals and fish, horn parings, hoofs, soot and wood ashes.

The general interest in artificial manuring developed much later. With the improvement of analytical chemistry chemists began to achieve some accuracy in determining the composition of plant tissues, and the end of the eighteenth and beginning of the nineteenth centuries saw the rise of a number of more or less detailed theories about plant nutrition. Amongst a number of famous names two stand pre-eminent, that of the German chemist Justus von Liebig, and that of the English agriculturist John Bennett Lawes. Liebig's theory was that the predominant factor in manuring with farmyard manure was the mineral matter thus contributed, and that the nitrogen supplied was relatively immaterial. In his view there was enough

nitrogen washed down in the form of ammonia in rain water to satisfy the crops' needs. Liebig argued skilfully but he did not put his views to the test of experiment. This Lawes did, starting the experiments on his farm at Rothamsted which have become world-famous. Liebig had over-estimated the supplies of atmospheric ammonia and Lawes, who maintained that nitrogenous nutrient was the important part of farmyard manure turned out to be right. He and Liebig never came to terms, and it is amazing to find Liebig trenchantly describing Lawes's experiments as of no value, and as proving just the opposite of Lawes's contentions. Lawes made other notable contributions to manurial practice. He started the manufacture of superphosphate and established a factory for its production.

Having demonstrated that nitrogen in farmyard manure was so productive of good yields he sought for other sources of nitrogen with which to experiment. At the time, the use of coal gas had become common practice for house and street lighting and in the process of manufacture large quantities of ammoniacal liquor were accumulated. These liquors resulted from the extraction of ammonia from the products of distillation of the coal and they were a serious nuisance to gas companies. Eventually sulphate of ammonia was recovered from them and became the bedrock of artificial fertiliser practice. In his classical field experiments Lawes used sulphate of ammonia in varying quantities, giving on some plots as much as 129 pounds of nitrogen per acre in this form. The results of the Rothamsted experiments provided a compelling argument for the use of artificial manures. It is no

slur on them or on the genius of Lawes and his collaborator Gilbert that at times they have been misused.

Fertiliser Practice and Soil Analysis

Once the custom of using fertilisers became general it was natural that the question of how much was necessary to obtain the best crops should be raised. What could be more apposite than to analyse the soil? There followed a period when manurial prescriptions were based on chemical analyses of the soil in respect particularly of the three main nutrients, nitrogen, phosphoric acid and potash. It would be wrong to suggest that this enthusiasm for soil analysis was altogether misguided and unproductive, but soil examination of isolated *ad hoc* samples is of comparatively little value except under special circumstances. There are so many other factors which play an important part in determining the efficiency of plant nutrition, and which may prove to be limiting factors in the growth of a crop. Moreover, in spite of endless refinements in method and much painstaking research, it is still impossible to determine with real accuracy by chemical methods what portion of a soil's nutrients are available to the plant. Even if this were determinable in terms of specific chemical compounds there still remains the problem of their rate of formation and removal from the sphere of operation of the plant's roots. The complexity of the processes involved has already been reviewed in Chapter V.

There is more hope from regional soil surveys which take into consideration many soil characteristics besides mere chemical analysis. Some, such as Hall and Russell's

classic survey of the soils of Kent, Surrey and Sussex have been eminently successful, but on the whole, from the point of view of their contribution to schemes of manurial practice they have been disappointing. In short, where such knowledge as technical methods can give has been wedded to careful observation of the growing crop and thorough knowledge of the natural environment, soil analyses have proved a useful ancillary weapon in the solution of agricultural problems. Their short range possibilities are frequently over-estimated. In general esteem the place of soil analyses for manurial advice has been superseded by direct field experimentation. Field experiments have their own disadvantages and some account of field experimentation will be given in a later chapter, but one advantage they do possess: they integrate all the factors which a purely analytical procedure must in the nature of things fail to do. Though soil investigations without field experiments are of limited usefulness for agricultural advisory work, there is no doubt that when soil surveys are more general, and soil types are adequately defined, the value of field experiments will be enormously enhanced by being referable to larger areas than those in their immediate vicinity.

Fertiliser Responses

The response to fertiliser treatment must necessarily vary according to conditions. We cannot deal precisely with all the factors involved, but something can be said of responses to varying doses. The soil nutrient content is obviously of first importance. Some soils in good heart show little or no response; others increase their produc-

tivity markedly when fertilisers are applied. The tea crop is a good illustration of efficient response to increasing doses of manure. The following table shows the yields and responses of tea to varying doses of nitrogen during a three-year period.

	<i>Yield</i> <i>lb. per acre</i>	<i>Differences</i>
N ₄₀ lb. per acre per annum	2,080	
N ₆₀ " "	2,373	293
N ₈₀ " "	2,678	305

It will be noticed that by increasing the dosage from 40 to 60 lb. of nitrogen per acre a response of 293 lb. has been secured for the extra 20 lb. of nitrogen a year. By giving a further 20 lb. of nitrogen another 305 lb. of yield are secured. In the light of the known errors of the experiment these two responses are equal and the experiment shows that yield increment is proportional to dose, over the particular range studied.

This is rather exceptional and contrasts with the behaviour of the same crop under incremental doses of phosphoric acid. During the same period the data for phosphoric acid applications were:

	<i>Yield</i> <i>lb. per acre</i>	<i>Differences</i>
P ₀ lb. per acre per annum	2,187	
P ₃₀ " "	2,453	266
P ₆₀ " "	2,490	37

Here the lower dose has given a useful response but the increased dose has resulted in only a small gain, so small that it is not possible with certainty to say that P_{60} is

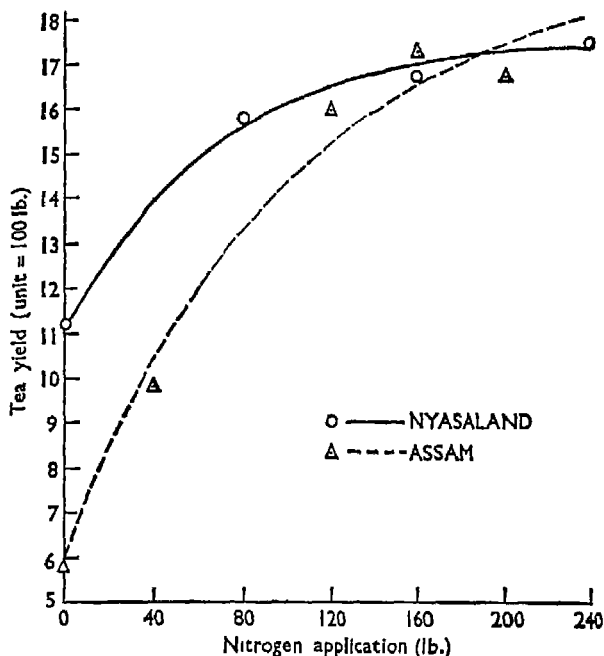


FIG. 6. The Law of Diminishing Returns.

better than P_{30} . This is a more usual feature to find in manurial experiments and practice. It illustrates in a severe form the operation of what is described as the "law of diminishing returns". An increase in dosage may give added crop but as the dosage increases the gain for a standard increment in nutrient is progressively less. Yield increments in other words are not usually propor-

tional to increase of fertiliser. The curve of yield plotted against dose is no longer a straight line but a curve something after the pattern of Fig. 6. Eventually, increase in manuring gives no further benefit and the yield becomes stabilised or, in some circumstances, actually decreases.

Yield response to a particular fertiliser is also dependent on the nutrient levels of other fertilisers present and of the soil itself. It frequently happens that the response of one nutrient is particularly sensitive to the quantities of other nutrients present. The following example is abstracted from the records of a potato experiment in the Annual Report of the Rothamsted Experimental Station for 1937. In this experiment both nitrogen and phosphoric acid were varied simultaneously.

TABLE IIIA. FERTILISER RESPONSES

ACTUAL

Yields of potatoes : tons per acre

<i>Sulphate of ammonia giving</i>	<i>Superphosphate cwt. of Phosphoric acid</i>		<i>Difference</i>
	0.75	1.50	
0 N	13.87	13.90	0.03
0.6 cwt. of N	15.62	17.23	1.61
Difference	1.75	3.33	

When phosphoric acid was given at the three-quarter hundredweight dosage, 0.6 cwt. of nitrogen as sulphate of ammonia gave a yield response of 1.75 tons. But when a dose of 1.50 cwt. of phosphoric acid was applied the yield

increment from the same quantities of nitrogen was nearly doubled. Turning to phosphate response : where no nitrogen was given an increase in phosphoric acid has been ineffective, but in the presence of 0.6 cwt. of nitrogen 1.61 tons more potatoes have been secured by resorting to the higher dose.

Another way of looking at these results is as follows. If nutrients acted independently, then the response to a specified dose of nitrogen and a specified dose of phosphoric acid, given at the same time, would be the sum of the responses to the two nutrients individually. Taking the first vertical column we see that the 0.6 cwt. of nitrogen gave a yield increment of 1.75 tons, and taking the top horizontal line, an extra 0.75 cwt. of phosphoric acid gave an increase of 0.03 which is negligible. Assuming that the effects are independent we can reconstruct the table as follows :

TABLE IIIB. FERTILISER RESPONSES

RECONSTRUCTED

Yields of potatoes : tons per acre

<i>Sulphate of ammonia giving</i>	<i>Superphosphate cwt. of phosphoric acid</i>		<i>Difference</i>
	0.75	1.50	
0 N	13.87	13.90	0.03
.6 cwt. N	15.62	15.65	0.03
Difference	1.75	1.75	

Actually the use of the higher dose of phosphoric acid with the addition of nitrogen gave 1.58 tons per acre more than would have been expected if the fertilisers had acted independently. This shows how dangerous it is to generalise on the subject of crop responses, without an adequate survey of dosage for all the fertilisers used acting simultaneously. Where the level of response to one fertiliser is affected by the level of dosage of another, the fertilisers are said to show "interaction" effects. This is a specialised term and has nothing to do with chemical interaction of the constituents of the manure.

Varieties of Fertilisers

Schemes of manuring generally embrace only the three main nutrient elements, nitrogen, phosphoric acid and potash. In areas where minor element deficiencies are known to occur, as for example in parts of Australia, traces of copper, zinc and molybdenum are included in fertiliser mixtures.

There is an immense variety of materials which can be used profitably as sources of manure and the choice is usually decided on the basis of cost first, and convenience second. If a farm or plantation is favourably sited near a source of material it may pay to use that material in preference to others which are usually regarded as superior. For example, the cheapest source of nitrogen is usually sulphate of ammonia. Its nitrogen percentage is high, its transport costs are therefore low, and it stores easily. In certain parts of Assam there are oil-seed crushing mills near to tea gardens and from time to time the oil cakes are frequently more economical as manure than the ammon-

ium salt. In Ceylon no such local circumstances favour the use of oil cakes, and the bulkier poonacs are invariably costlier per unit of nutrient than the simpler inorganic fertilisers.

The following account of various types of fertiliser is not exhaustive but includes most of those that are in common use in local and plantation agriculture in tropical countries.

Nitrogenous Fertilisers

These fall into two classes, (1) the relatively simple chemical compounds which are either mined as such, or are the product of chemical industry, and (2) the residues from processing of animal and vegetable products. The latter have their nitrogen in a more complicated form (protein) and may contain appreciable quantities of potash and phosphate also. An unending controversy has been carried on as to whether the second class, being "natural" products are better than the former. The emphasis laid on the arguments in favour of the "organic" fertilisers has varied from time to time. With the argument that because a fertiliser comes from a natural product it must be superior it is difficult to contend, except after long and large-scale comparative experimental work which has not yet been done. It is known that plants cannot make use of the nitrogen in these products till it has been broken down into simpler forms. Accordingly discussion tends to centre round two main viewpoints. In favour of organic artificials it is urged that they provide valuable organic matter. In terms of bulk this argument is specious because the quantities used seldom exceed half a ton per

acre. The top nine to twelve inches of soil weigh approximately a thousand tons so the contribution is negligible especially as the existence of the manure as "organic matter" is very short-lived. A second argument is that such manures release their nitrogen gradually and cater for the needs of the plant at a rate appropriate to its powers of absorption. The strength of this contention is weakened by the fact that the carbon/nitrogen ratio of these manures is low—somewhere in the neighbourhood of 5-7, and according to the evidence set forward in Chapter V they decompose rapidly and mineralise their surplus nitrogen within a month or two. Experiments extending over fifteen years on tea for instance give no support to the view that they differ appreciably in respect of gradual availability from sulphate of ammonia. Once mineralisation is in full swing the risk of loss in drainage is on a par with other fertilisers.

Organic manures certainly stimulate micro-organic activity in the soil, but as against this may be set the fact that a reasonable green manuring programme does this more efficiently and at less cost. The most cogent argument in favour of organic manures is that since they come from previously living tissues, they contain besides the main nutrients, the small amounts of less conspicuous but essential elements necessary for normal plant growth and they safeguard the supplies of these elements wherever they are used. In the last resort the moderate view is that they resemble inorganic fertilisers in their action more nearly than a bulk manure or compost, and the decision for or against their use must remain, as previously stated, a matter of cost and convenience. The organic manures are

certainly more foolproof in use and are free from disadvantageous secondary effects which may in specific instances attend the use of inorganic fertilisers.

Inorganic Fertilisers

Sulphate of ammonia contains 20·6 per cent of nitrogen and is either a by-product of gas works or is manufactured synthetically from the nitrogen of the air. It is sold either as a fine crystalline product which tends to cake on storage in damp atmospheres or in a granulated form with particles about the size of rice grains. The latter type is superior in handling and storage properties. It is freely soluble in water, but the base exchange capacity of the clay in soil prevents its ready loss. Some crops can use its ammonia direct, but by bacterial action it is readily converted to nitric acid which combines with the basic elements of the soil, calcium, magnesium, potassium, etc. Because the "basic" portion of the salt "ammonium" is changed into an acid which has to recombine with the bases already present in the soil it makes these bases more mobile, for all nitrates are soluble. In course of time therefore drainage and seepage depletes the soil of bases, and the soils on which sulphate of ammonia is continually used become progressively more acid. It is therefore called a "physiologically" acid fertiliser though in its original form, being a normal salt, it is neutral. On crops that are intolerant of acid conditions therefore it can have deleterious effects unless the obvious precaution of liming is attended to.

Nitrate of soda contains 15-16 per cent of nitrogen. It is mined in various places, particularly Chile (whence its

name Chile saltpetre) and is the result of the oxidation of deep layers of bird guano laid down in the remote past. For this reason it contains traces of most of those minor elements which have recently sprung into prominence in agricultural literature. Nitrate of soda is soluble and its nitrogen is immediately available to the plant. Since the nitrogen is present in acid radicle form there is no base exchange activity to retain it. What is retained is the sodium. Accordingly, drainage losses are liable to be higher with nitrate than with the ammonium salt, and the tendency of soils to which it is applied is to decrease in acidity. A soil highly charged with sodium becomes very sticky and impervious to water. As ordinarily used, there is no fear of soils deteriorating from this cause. In damp climates nitrate of soda picks up moisture and does not easily store.

Ammonium nitrate contains 32-35 per cent of nitrogen. This is a very concentrated salt containing nitrogen in both its "basic" and acid radicle parts. In its manner of behaviour in soil it is half way between sulphate of ammonia and nitrate of soda. It is made in fine crystalline powder form, and also in granules. The former type is very difficult to store and handle because the salt is very deliquescent. The granular form is protected by being oiled and dusted with kiesselguhr, and if stored in damp-proof containers keeps reasonably well even in the tropics. Its use in mixtures of manures is easier, and will be dealt with in the section devoted to manure mixtures. When mixed with about equal quantities of chalk, and granulated, ammonium nitrate is sold as nitro-chalk with a nitrogen content of $15\frac{1}{2}$ per cent. In this form it keeps well and is a very useful fertiliser but is not in general use in the tropics.

Ammonium sulphate-nitrate is compounded of ammonium sulphate and ammonium nitrate in approximately equimolecular proportion and has a nitrogen content of 26 per cent. In Germany, the country of manufacture, higher nitrogen levels, which would involve a greater proportion of the nitrate, are prohibited as a safety precaution against the possibility of detonation.

Organic Manures

The nitrogen contents of organic manures are generally low. They are waste products derived from the processing of more valuable commodities and are of diminishing importance. They fall into two classes, the poonacs from oil seeds after extraction of the oil and the offal of slaughter houses.

Oil Seeds. Edible protein is a valuable commodity and if oil seed residues have a reasonably high protein content (e.g. ground-nut cake) or a high carbohydrate content (e.g. coconut poonac) they are in demand as cattle food. Before World War II the plantation industries of Ceylon and S. India made use of ground-nut residues, containing 7-8 per cent of nitrogen, as a fertiliser. Since this nitrogen is equivalent to almost 50 per cent crude protein it became too valuable to use as a manure and ground-nut poonac is no longer sold as a fertiliser. Those poonacs that are offered have nitrogen contents between 3 and 4.5 per cent, the best known being Castor Cake. The slaughter-house products have a higher manurial value. The most commonly used are as follows.

Blood Meal. The nitrogen content varies between 11 and 12.5 per cent. This is a useful foolproof manure more especially suitable for horticultural and other crops with a high cash value per acre. It contains some calcium, sodium and phosphate but not enough to be valued.

Horn and Hoof Meal has an average of 13 per cent nitrogen. It is one of the earliest used fertilisers in the modern sense of the word and is similar in action to blood meal, though not so quickly mineralised.

Animal Meal, a heterogeneous slaughter house waste is of poorer quality and contains about 7 per cent of nitrogen.

Further examples of organic manures will be described later when compound fertilisers are considered.

Urea is a product of animal metabolism and is found naturally in urine. It is of special scientific interest because it was the first "organic" compound, hitherto associated exclusively with living organisms, to be synthesized in the laboratory. The urea of commerce is made from cyanamide and has largely replaced the latter as a fertiliser. Its nitrogen content (46 per cent) is higher than that of any other nitrogenous fertiliser. It decomposes in, or on, moist soil to form ammonium hydroxide which is neutralised by soil acid constituents. The decomposition is so rapid that agriculturally it behaves like an inorganic nitrogenous fertiliser.

The main advantage of urea as a fertiliser rests on its high concentration which makes it attractive where it is subject to high haulage as in the interior of Africa. It has certain disadvantages of which the chief is its hygroscopic nature, which makes it unsuitable for long storage in

humid climates. In the manufacture of urea a small quantity of an impurity, biuret, is formed and this is toxic to plants. This toxicity is dangerous to germinating seeds but not of any account when it is used as a top dressing to developed plants. The biuret decomposes in the soil, and urea should therefore be applied some time before sowing seeds.

Comparisons of efficiency using sulphate of ammonia as the standard are slightly in the latter's favour. The poorer performance of urea is probably due to two causes; first the rapid production of ammonia which in sufficient concentration is itself toxic, and secondly to the escape of this ammonia eventually into the atmosphere. Both these drawbacks are less prevalent on acid soils. Bearing these points in mind urea, properly used, is a valuable addition to the range of nitrogenous fertilisers.

Potassic Fertilisers

The two in general use are:

Sulphate of potash containing 48 per cent of potash. The powdery consistency of this fertiliser makes it easy to use and it stores well. It is rather more expensive than the muriate.

Muriate of potash (Potassium chloride) contains 50 or 60 per cent of potash. It is produced either by refining mined deposits of potash salts (Kainit or Sylvinite) or by extraction from deposits from the Dead Sea. In tropical use it is apt to be rather deliquescent but not sufficiently so to prevent its extensive use.

The lower grade salts of potash, Kainit (16 per cent) and Sylvinite (18-20 per cent), are not in general use. The

former contains appreciable quantities of magnesium sulphate and both are laden with common salt.

Phosphatic Fertilisers

Mineral phosphate. The basic material for many simple phosphatic fertilisers is mineral rock phosphate. Beds of this occur in various parts of the world as a result of the metamorphosis of the shells of cretaceous animals. In North Africa and in North America and in some of the Pacific Islands (Nauru) and at Christmas Island in the Indian Ocean the deposits are extensive. The crushed mineral is sold as mineral or rock phosphate under a variety of styles which usually denote its origin. It contains 28–30 per cent phosphoric acid. Other mineral phosphates are sold under trade names and various claims are made for their superiority, such as the content of radioactive material. Fairly extensive trials indicate that it is best to value these in terms of their phosphate content only.

Mineral phosphates are insoluble in the ordinary sense of the term. In wet climates on acid soils they give satisfactory results comparable with those of other phosphatic fertilisers.

Superphosphate is marketed in two grades with 18 and 42 per cent phosphoric acid respectively. The latter, referred to as concentrated superphosphate, is the more widely used in the tropics. Originally superphosphate was made by treating bone charcoal with sulphuric acid, but mineral phosphates soon replaced the bones. Their use was the basis of Sir John Lawes's patent for the manufacture of superphosphate of lime. The action of sulphuric acid produces compounds readily soluble in water. For the

concentrated superphosphate, phosphoric acid is used as the converting material. Although the mineral phosphates are treated with acid, the resulting product is not acid and the continued use of superphosphate does not affect the soil reaction adversely. The phosphate of superphosphate is more readily available than that of mineral phosphates, but it is probable that in the soil all phosphatic manures revert to the less soluble apatites. Consequently the penetration of phosphates in the soil is not very marked.

Basic slags. The other main source of phosphatic manures is slag from steel works. The presence of phosphates in steel makes it brittle. In converting pig-iron into steel basic material such as lime and magnesia and a flux in the form of fluorspar are used to remove phosphate. The result is a slag which contains the phosphate and which can be separated from the steel. Slags vary in their phosphate content according to the process by which the steel is made. Their phosphate also varies in solubility. One cause of this is the fluorspar that is added to make the slag run. The phosphatic compound fluorapatite is highly insoluble and slags rich in fluorine are consequently of low solubility. A further factor which determines usefulness is fineness of grinding. This applies equally to mineral phosphates. The solvent action is a surface action and, as explained heretofore, a large surface in comparison to bulk accelerates solvent and chemical action generally.

Slags therefore should be viewed with respect to phosphoric acid content, solubility, and fineness of grinding. For determining solubility it is usual to use, not water, but a 2 per cent solution of citric acid. This weak acid was supposed to simulate the soil solution effect, but

actually it has no importance of this kind and its action is quite empiric. Its continued use is a matter of convenience and convention.

Slags range from 8 to 18 per cent in phosphoric acid content and from less than 40 per cent to 80 per cent in solubility. They contain appreciable amounts of free lime. They are not widely used in tropical practice. Their chief merit lies in application to poor pasture in which they encourage the growth of native leguminous species, notably wild white clover in temperate regions.

Compound Manures

Some fertilisers contain more than one of the major plant nutrients. Of the traditional kind two, fish guano and bonemeal are still in use.

Fish Guano

This is derived either from non-edible fish dried and ground whole, or from edible fish from which oil has been extracted for commercial purposes. The pulverised flesh of whales is also included in this category. The amount of nitrogen and phosphate these guanos supply varies between 4 and 7 per cent of both nutrients.

Bonemeal

Most bonemeal is steamed bonemeal prepared by crushing bones from which fats, gelatine and glue have been extracted. The removal of these substances gives a product of better physical condition for distribution. Bonemeal contains 22 per cent of phosphoric acid and 3 per cent of nitrogen.

Straightforward chemical salts are also used as compound fertilisers mainly as components of various proprietary fertiliser mixtures but in Asia they have a small sale for direct use. Two are listed in fertiliser catalogues.

Ammonium Phosphates

There are three of these according as one, two or three of the hydrogen atoms of orthophosphoric acid have been replaced by the ammonium radicle. As prepared for the fertiliser trade their nitrogen and phosphoric acid content depend on whether the product is substantially confined to one of the three salts or to a mixture in varying proportions. Examples of the guaranteed analyses of the percentage grades offered are (a) N 20, P_2O_5 35; (b) N 16, P_2O_5 20; (c) N $_{25}$, P_2O_5 48.

Potassium Nitrate (saltpeter) is sold in the grade K_2O 44 per cent, N 13 per cent.

Fertiliser Mixtures

The foregoing sections have described some of the properties of artificial fertilisers which are important when choosing them for manurial treatment of soil and crops. When several ingredients are combined there are other considerations to take into account in order to produce a satisfactory mixture.

Two of great importance are to provide a mixture that will remain in a friable condition when stored, and that will not lose valuable nutrients as a result of interaction of the constituents. Deliquescent salts can only be used in moderate amounts and with special precautions (vide ammonium nitrate), and ammonium salts must not be

brought into contact with basic substances under moist conditions because if they are, they will be decomposed and lose their nitrogen as ammonia gas.

In the following table the individual ingredients are arranged to show their combination in pairs. At the intersections of rows and columns the signs show whether under tropical conditions they can safely be mixed and stored.

TABLE IV
Guide to Storage of Fertiliser Mixtures

	<i>Sulph. Ammonia</i>	<i>Nit. Soda</i>	<i>Nit. Ammonia</i>	<i>Super.</i>	<i>Min. Phosphate</i>	<i>Slag</i>	<i>Potash Salts</i>	<i>Bone Meal</i>	<i>Blood Meal</i>	<i>Oil Cakes</i>	<i>Urea</i>
Sulphate of ammonia	-	†	†	*	*	†	*	*	*	*	†
Nitrate of soda	†	-	†	†	†	†	†	*	*	*	†
Nitrate of ammonia	†	†	-	†	†	†	†	*	*	*	†
Superphosphate	*	†	†	-	†	†	*	*	*	*	†
Mineral phosphate	*	†	†	†	-	*	*	*	*	*	†
Basic slag	†	†	†	†	*	-	*	†	†	†	†
Potash salts	*	†	†	*	*	*	-	*	*	*	†
Bone meal	*	*	*	*	*	†	*	-	*	*	†
Blood meal	*	*	*	*	*	†	*	*	-	*	†
Oil cakes	*	*	*	*	*	†	*	*	*	-	†
Urea	†	†	†	†	†	†	†	†	†	†	-

Key

* May be safely mixed

† May be mixed for immediate use

‡ Not to be mixed

Granulated Fertilisers

Finely ground fertilisers are unpleasant to handle both in the factory and in the field. They have been almost entirely replaced by granulated materials.

The advantages of granulation are largely self-evident. Particles larger than a pin head are less likely to cake and deteriorate in storage than fine powders and crystals. They can be more easily drilled and more accurately placed. Windy weather is less of a nuisance when granulated fertilisers are distributed. Granules must be strong enough to resist fracture when they are handled, mechanically or otherwise, and when they are running through a drill. To ensure this it has been suggested that the standard of strength required should be a crushing pressure of not less than 100 lb. per square inch. Control of moisture content is essential and not more than 2 per cent should be tolerated.

The materials commonly used in the preparation of granulated fertilisers are ammonium sulphate, ammonium sulphate-nitrate, mono- and di-ammonium phosphate, superphosphates (single and concentrated), potassium sulphate and potassium chloride.

This catalogue includes four different sources of nitrogen at four different concentrations, and, in a corresponding manner four phosphatic variants and two of potash. This variety gives great flexibility in the construction of fertiliser prescriptions of the standard N P K type. Using suitable combinations of quantity and quality a very wide range of fertilisers can be offered in a standardised form. Granulated fertilisers commonly provide anything from 30 to 50 units of nutrient per

ton. At this latter concentration half the bulk of a consignment consists of the required nutrient. The saving in handling, storage space and transport charges is obvious.

Fertiliser Placement

An increasing amount of work is being done to unravel the problems of fertiliser distribution and placement in relation to the growing crop. We have spoken of fineness of grinding for slags and mineral phosphates as being desirable, but on the other hand have indicated that granulation is beneficial for other reasons. The two factors are not mutually exclusive because the artificially granulated products, if they are insoluble powders can be prepared from finely ground particles. The little work that has so far been carried out shows that granulated fertilisers are as efficient as the older fine crystal or powder types. Investigations on placement in the field have been confined mainly to annual crops manured at seeding time. The findings are slightly in favour of sowing fertilisers in narrow and fairly concentrated bands on either side of the drilled seed. Mixing fertilisers with the seed has not been found to be good practice. As far as the evidence goes, it appears that phosphatic fertilisers distributed in concentrated zones produce higher yields than broadcast fertilisers, provided that direct contact, which may affect germination and seedling establishment, is avoided. Placement of potash manures is less markedly beneficial, but results are promising. Nitrogen placement is not of over-riding benefit. Time of application is of greater importance. Similar trials for perennial species are

desirable, but on general principles the same kind of results may be anticipated. The dangers arising from contact between root and fertiliser are not so great with perennial crops. The writer has seen the young shoots of tea withered and browned as a result of grossly careless fertiliser placement, but the damage was not severe. In following up these observations, test bushes were supplied with compact parcels of sulphate of ammonia at a rate of 2 lb. per bush. No harmful effects were produced. In the process of "envelope" forking on tea plantations, whereby a V-shaped pocket or envelope is made in the soil, some estates purposely distribute concentrated fertilisers in these pockets without deleterious effects. Other estates place fertilisers in concentrated semi-circular bands above the bushes. The tentative inference, from the work on fertiliser placement just quoted, is that except for very young plants of limited root range, the practice is likely to be a beneficial one.

Value of Artificial Fertilisers

The list of fertilisers given earlier in this chapter shows that some fertilisers contain more of the desired nutrient than others. Any attempt therefore to compare the prices of fertilisers must be carried out not in terms of equal quantities of the fertiliser but of the nutrient or nutrients they contain. Moreover, some convention is needed to ensure that the nutrient itself is always referred to in the same terms. Formerly, confusion was caused by classifying nitrogenous manures in terms of either nitrogen or ammonia, the latter giving a higher figure than the former for the selfsame sample. It is now customary to refer to

the composition of a fertiliser in terms of nitrogen: N, phosphoric acid: P_2O_5 , and potash: K_2O . These terms and their chemical formulae are only convenient symbols. They do not imply that elementary nitrogen which is a gas, or potash K_2O , an artificial and ephemeral compound, are present in the fertiliser. To call P_2O_5 phosphoric acid is actually to use a misnomer. There are a number of phosphoric acids, all of which contain the combination P_2O_5 in their molecular structure. It would be more logical to use the simple elements N, P and K, but as the break with tradition would cause further confusion the old terms are maintained.

The unit by which the value of a fertiliser is determined is 22.4 lb., i.e. one-hundredth of a ton, of nitrogen or phosphoric acid or potash respectively. At first sight this seems a clumsy unit, but actually it is very simple. The composition of fertilisers is reported on the percentage scale and it makes calculation easier if we stick to a percentage scale for the price unit; for to determine the cost of a unit of the nutrient, all that is necessary is to divide the price per ton by the percentage composition as regards nutrient. The following example will make clear how the comparisons are made.

	(a)	(b)	(a/b)
	<i>Price per ton</i>	<i>per cent</i>	<i>Unit price</i>
	<i>Shillings</i>	<i>nitrogen</i>	<i>of 22.4 lb.</i>
			<i>of nutrient</i>
Sulphate of Ammonia	471	20.6	22.9
Castor Cake	322	4.5	71.5
Blood Meal	1260	12.0	101.0

In price per ton, sulphate of ammonia is dearer than castor, but in price per unit, i.e. price for equivalent quantities of nutrient, sulphate of ammonia is the cheapest.

Those fertilisers that are compounded of more than one nutrient are not so directly comparable. To illustrate the method of making a valid comparison fish guano will be taken as an example. This fertiliser supplies both nitrogen and phosphoric acid so it will be useful to compare its cost with a mixture made up to the equivalent manurial value from the standard ingredients ammonium sulphate and concentrated superphosphate. The data and calculations involved are as follows.

<i>Fertiliser</i>	<i>Cost per ton</i> Shillings	<i>Analysis per cent</i>		<i>Unit cost</i>	
		N	P ₂ O ₅	N	P ₂ O ₅
Fish Guano	622	7	4.5	—	—
Ammonium sulphate	471	20.6	—	22.9	—
Conc. Super	757	—	42	—	18
Cost of 7 units of N. as Ammonium Sulphate 7×22.9					
= 160.3					
Cost of 4.5 units of P ₂ O ₅ as Conc. Superphosphate					
$4.5 \times 18 = 72.9$					
		Total		Sh. 233.2	

The equivalent nutrient value as regards nitrogen and phosphoric acid could be had from a mixture of ammonium sulphate and superphosphate for Sh. 233 or 37.5 per cent of the cost of fish guano. This is a high premium to pay for fish guano unless this manure has some special virtue or convenience.

Trace Elements

Reference has been made (p. 6) to trace elements which are present in the soil in minute quantities only, often less than one part per million in soluble form. They are nevertheless essential to healthy plant growth and by the process of continual cropping are liable to be reduced to deficiency levels. The most important are copper, cobalt, boron, zinc, molybdenum and sulphur.

The primary cause of these deficiencies lies in the way the earth's rock crust has crystallised on cooling. Crystals have an intricate atomic structure, and, in the various conditions prevailing at the time of formation, some elements failed to fit into the organised pattern, and remained concentrated in the deep uncrystallised mass, rather as impurities remain in the mother liquor when salts are purified by recrystallisation.

It is dangerous to add trace elements to soils and fertilisers indiscriminately, because excess is as harmful as deficiency. Agriculturists and horticulturists have become trace-element-minded, and in order to clarify the subject two propositions may be stated. First, since the deficiency is of geochemical origin, it is likely to arise over considerable areas and not as isolated and occasional instances. Second, since deficiencies constitute limiting factors, they cannot logically be invoked where responses to major nutrients are satisfactory.

CHAPTER XI

FIELD EXPERIMENTS

KNOWLEDGE of the soil and its properties is necessary if the best agricultural use is to be made of the land, but as has been explained earlier, laboratory experiment and analysis can only play a limited part in the scientific approach to agricultural problems. They will often suggest new treatments and processes and, in particular instances, they may track down deficiencies and defects which are at the root of crop failure. In addition to such exploratory and explanatory work, experiment in the field is needed, and it is from this kind of work that modification in cultural practice is generally and finally brought about.

Objections to Modern Field Experiments

Beginning about 110 years ago, field experiments have gradually grown in complexity, which has become increasingly noticeable in the last twenty years. Whereas at the beginning of the century it appeared possible to inspect a series of experimental plots and a tabulated statement of their yields and arrive at a reasonable estimate of causes and effects without a strictly scientific training, the position now is that such inspection and consideration leaves little except a confused impression on the practical agriculturist. The reasons for this are fairly plain: whereas the older experiments were usually confined to a few plots with simple variations in treatment from which

direct comparisons were readily available, modern experiments are vastly complicated in their treatments ; have several factors varying at the same time, and are frequently composed of anything from 50 to 100 plots. It is frankly impossible to keep in one's mind's eye the level of performance of a dozen plots devoted to one treatment, for mental comparison with another dozen differently treated, especially when with apparent perversity, the experimentalist shows no nice systematic arrangement of his comparisons.

Those who, like the author, have had the task of introducing modern experiments to practical agriculturists, have found that their constant objections are as follows :

- (1) The plots are too small to give an adequate answer to the agricultural questions that are postulated, especially when costs are considered.
- (2) Space occupied by replication would be better used in providing a few reasonably sized plots.
- (3) The conception of an " error " and interpretation of results with respect to it, is virtually beyond the grasp of the practical man, and the element of " randomness " in plot distribution frequently merely annoys him.

In reply to these criticisms the experimenter replies that advice tendered as a result of experiments frequently involves a farm or estate in considerable expenditure, and the experimenter naturally wants to be sure of his facts. The complexity of modern experiments is not a fad on his part, but an attempt to improve the accuracy of his findings. He might also say that it is not altogether reasonable for the agriculturist to expect that the technique by which

he strives to attain this accuracy should be plainly understood in lay circles. We do not expect that we shall understand the complexities of technique used by a medical man in diagnosis and treatment, or by the chemist in the preparation and analysis of useful drugs, or by the bacteriologist who guards the purity of water supplies or prepares a serum to control an epidemic. In brief, the field experimentalist has a right to expect that he shall be accorded the same degree of confidence in his purely technical efforts that other scientific workers are given in theirs. This does not absolve him from doing what he can to enlighten his clientele about such matters. What success the following explanations may have it is hard to conjecture but an attempt will be made to give some account of the reasons that lie behind the methods employed in modern agricultural experiments.

Causes of Error in Field Experiments

Let us suppose that it is desired to test the effect of two treatments, A and B, in a field experiment. There are two obvious approaches to the problem. We may select a piece of land on which to grow whatever crop we are interested in, and apply treatment A to that land for one or more seasons, carefully recording yields or other relevant data during the course of the experiment. Then we can change over to treatment B and continue it for the same length of time. The one clear advantage this method seems to have is that both treatments are carried out on the same area, but it is an illusory advantage. Treatment A may change the soil properties, so that when B is started the soil is not identical in condition with that ruling when

A was begun. If it is a manuring experiment, the question arises as to whether there are any residual effects from A that will complicate the later results : effects which will eventually and erroneously be ascribed to B. By far the most serious disadvantage is the fact that weather conditions during the A treatment may be, and most likely will be, quite different from those obtaining during the later B period. We shall finish up with results which, if they show a difference between A and B, are due partly to soil conditions, partly to climate, and partly to the difference in treatments ; but it will be impossible to assess the part played individually by any of the three factors.

The second method is to choose two pieces of land presumed to be as alike as possible and to test the effect of A on one and B on another. However careful the choice, one thing is certain, the productivity of the one plot before treatment will not exactly correspond with the productivity of the other. The climatic complication is eliminated, but the results from the plot carrying A treatment will be the combined effect of treatment and original fertility, and the same applies to the plot carrying treatment B.

The most reasonable way out of this dilemma is to try the treatments A and B not on one plot each, but on a number, be it 5 or 10 or 20, in the hope that the average of the replications will show less deviation between the two sets than single plots would have done. This is entirely sound practice, but though it reduces the chances of ascribing to treatment what should rightly be ascribed to soil heterogeneity, it does not entirely eliminate the trouble.

By way of illustration let us suppose that we have two marksmen firing six shots at a target in a grouping test.

The first marksman's shots would show a certain scatter about the bull's eye and it would be possible to draw a circle round the holes in the target to include them all. The second marksman's efforts would be similarly treated. It might happen that the second circle would fall entirely within the first by a considerable margin, and we should conclude that he was the better shot. But suppose that the two circles almost coincided. On that target we could still say that one had shot better than the other on that occasion; but it would be rash to say that in another identical shoot the man with the inner circle would still remain the victor. More probably, in this test the circles would intersect and the problem of deciding which was the superior marksman would be greatly complicated.

Mathematical Errors as Measures of Representativeness

Returning to the consideration of field plots, let us suppose that we have twenty plots to divide between two treatments, A and B. We may arrange the treatments in an orderly succession, A B A B A B etc., but if there is a fertility gradient in our land making it less productive from left to right, this arrangement will consistently favour the results from the A plots. Instead of a regular arrangement we can adopt a random one, placing ten tickets marked A, and an equal number marked B in a hat, mixing them up and drawing them out in turn. Yield results from plots treated in this way might very well show that the average of the B treatments was better than that of the A's. They would undoubtedly show that there was a considerable range between the highest and lowest values for plots treated alike, and that when the range for A's and

B's was compared there was a certain amount of overlapping. Faced with the undoubted fact that the plots of the B treatment, supposedly treated alike, can vary by a considerable amount, so that some of their yields coincide with, or are even less than, some of those of the A group, can we justifiably make the assumption that the difference in their averages, favouring B, can be relied on ?

The random arrangement used in this trial is only one of many. If we had the chance of repeating the experiment with a different grouping we should find that the yields of replicates continued to show more or less scatter, and that the averages showed a similar but less marked disparity. We might even find that the relative superiority of B was less pronounced or that B now appeared less favourable than A. From a series of such trials we could derive a general average from which those of the individual experiments deviated, sometimes in a positive and sometimes in a negative direction ; and it would be clear that by resorting to replication and random arrangement we have done something to eliminate bias in either direction from vitiating the answer to the question " Is B treatment better than A or *vice versa* ? " What is further required is a precise means of assessing the representativeness of the results, or conversely the variability, so that we can discover how much of it is due to chance, and use that knowledge to interpret the differences in average yields that the various consciously applied treatments appear to produce. Mathematical statistics provide methods for doing this by studying the variation between replicates, i.e. between plots that, as far as conscious effort is concerned, are treated alike. Let us look more closely at a

straightforward example of random variation so as to get some notion of how it works.

Suppose we have a considerable number of objects of the same type that we wish to measure. They may be field plots for which the yield is known, or heights of boys of equal age, or weights of paper clips of a reputedly standard size. In the process of measurement it will become evident that there is definite variation between the individual units. Let us take as an example the weights of 200 paper clips. In an actual experiment it was found that the lowest weight encountered was 380 units and the highest was 481.

If we divide this range up into say ten equal parts we can then count the number of clips that fall within the dimensions of each compartment. It will be found that at the extreme ends of the range the numbers, or frequencies as they are called, are low and towards the middle they are high, as shown in the following table.

TABLE V

Distribution of weights of 200 paper clips of standard size

	<i>Range Units of weight</i>	<i>Frequency</i>
Compartment 1	370-382	2
2	382-394	0
3	394-406	7
4	406-418	16
5	418-430	55
6	430-442	64
7	442-455	39
8	455-467	10
9	467-479	6
10	479-491	1

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In the form of a graph these values can be plotted as columns, the bases of which are the compartment dimensions, and the heights the frequencies. The result is shown by the shaded columns in Fig. 7. On the base line there is an arrow which marks the average weight of the

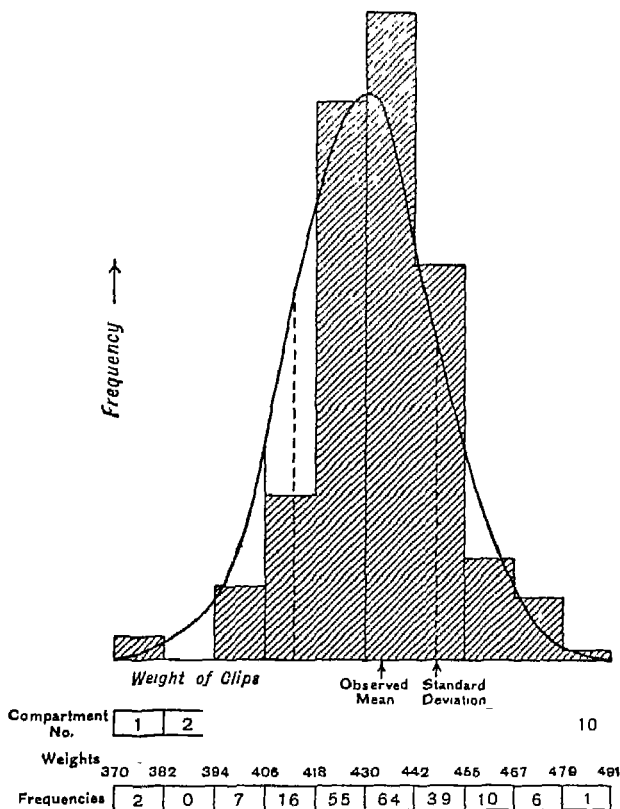


FIG. 7. Distribution Diagram of Weights of 200 Paper Clips of same reputed Size.

200 clips. It is at once obvious that the diagram is fairly symmetrical about this value. Actually there are 103 weights below the average value and 97 above it.

This group or "population" of paper clips as we shall call it, is actually only a small one, and a better decision on the question of symmetry would be obtained if we took a thousand or ten thousand and made our compartment ranges smaller and their number greater. We should then have columns building up in smaller steps and looking much more regular, something after the manner of Fig. 8

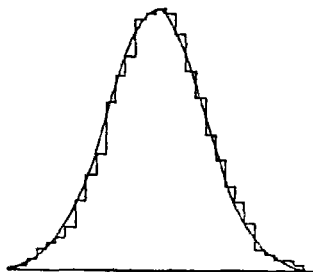


FIG. 8. Distribution Diagram and Theoretical Curve.

Supposing now that we are not limited by number of paper clips and the compartment sizes are made smaller and smaller. The steps would tend to become less and less noticeable until it would be possible to represent the shape of the whole boundary by a smooth curve. Such a smooth curve is drawn in Fig. 7 superimposed on the columns. It represents on the same scale the ideal distribution of the frequencies of the paper clips. It is perfectly symmetrical about the dividing line between the fifth and sixth compartments, which on the weight scale is marked 430, which is not very different from the mean of

the 200 actual weights (434.3). If we took a different 200 clips and constructed another diagram of the same type it would be found that it was similar but not identical. This distribution diagram and its ideal form shown by the curve, is typical of many that are obtained when a random selection is made from a large population of objects or measurements. The curve, which is called the "normal" curve, has very interesting properties, two of which, in addition to those regarding symmetry previously mentioned, are specially important.

If we travel from the peak downwards to the right, the curve is first of all convex to the base and then changes to concave. If we fix the point where the change-over takes place and drop a perpendicular from this point to the base, this line indicates a certain value on the weight scale. A similar point can be found travelling to the left, and these two points will be equidistant from the centre or mean value. The particular value obtained is an important statistic and is called the *standard deviation*. It is measured from the centre and is either positive or negative according as it is to the right or left of the mean. The important thing about it is that if we know the mean value of the population and its standard deviation, we can draw the ideal curve without recourse to any other measurements. In other words, the normal curve can be expressed in terms of a mathematical equation, and any particular variation of it to fit any actual data can be derived by using the appropriate values of the mean and standard deviation.

The second property of the normal curve is the one which makes its usefulness apparent in problems such as are answered by field experiments. Suppose at the upper

limits of the third, fifth and seventh compartments we draw perpendiculars up to the boundary curve of Fig. 7. The whole area confined between the base and the boundary will then be divided into four sections. Two of these will be exactly similar tails, and two will be exactly similar middle portions. Now the values 3 and 7 on the base represent equal deviations from the mean value 5, one positive and one negative. What are the odds that a particular paper clip chosen at random will differ from the average by more than 25 units of weight, i.e. will fall within the tails and be less than 406 or greater than 455 units in weight? Or put in another way—How many of the 200 clips should we expect to have weights less than 406 or greater than 455? The answer is given by comparing the areas of the tails with the area of the complete whole. The tails comprise just over 14 per cent of the whole area so that we should expect that there would be 28 of the 200 clips of the dimensions stated. Actually, as the frequency numbers show, there were 26.

In dealing with field experiments we are usually comparing the means of yields produced by different treatments. The same sort of curve is applicable to these means and to differences between them. Because we have replicated plots we can calculate a value which is an expression of the standard deviation of the population from which our mean differences are derived. It will not be absolutely accurate because the population is always a limited one, but it will allow us to make some useful comparisons. Let us draw the normal curve again and this time mark on the base line the values of the standard deviation, twice the standard deviation, three times etc.,

as is done in Fig. 9. The proportions of the whole area cut off in the tails to the right and left of these values are for 1 S.D. (standard deviation), 31.73 per cent; 2 S.D., 4.55 per cent; 3 S.D., 0.27 per cent.

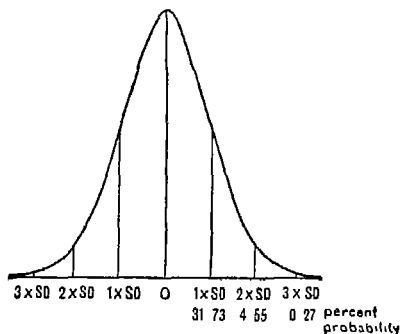


FIG. 9. Areas remaining in tails and probabilities corresponding to them (in percentages).

Obviously the odds that the difference between two means in our experiment will, by mere chance, exceed three times the standard deviation are very small since the area left in the tails is so minute compared with the whole. 0.27 per cent is 27 in 10,000 or 1 in about 370. If then we find a difference between two means in an experiment as great as 3 S.D. the odds that this is pure chance are negligible. That difference then must be due to something other than chance, and we are justified in ascribing it to the difference in treatment. By applying the favourable agricultural treatment we have altered some of the units of our population and created the elements of a quite different population, and the distribution curve appropriate to this population is similar to the original but not identical.

The foregoing example shows that if from any population, or random samples of it, we derive the averages we require and the standard deviation relevant to them, which we can use as a *standard error*, we shall be able to calculate the odds against any mean difference being due solely to chance. If the odds against chance are high we shall call the mean difference a *significant difference*, and shall place considerable reliance on it. All the necessary calculations can be made by simple arithmetical processes without actually constructing a diagram of the sort shown in Fig. 7. The conventional practice is to regard odds of 19 to 1 against the differences being fortuitous, as being high enough to justify reasonable confidence in the experimental results. Below this probability we should say, not that the difference observed has no connection with treatment, but that the accuracy of the experiment is insufficient to make it a safe bet. Anyone who has carried out large numbers of field experiments has at some time had the experience of lighting on a difference that has been produced by the unlucky one chance in twenty, and consequently experimenters prefer odds of 99 to 1. Statistical methods do not give absolute certainty, but their great advantage is that the decisions they lead to are independent of purely personal bias. They prevent an experimenter from deceiving himself that he has made a discovery, and from passing it on as a proven fact.

Practical Value of Small-Scale Experiments

To employ this objective method for the interpretation of experimental results, it is seen that the arrangement of plot treatments must involve an element of randomness

and that treatments must be replicated. We have yet to consider the question of plot size and to answer the objection that with field experiments of this kind the plots are too small to be of practical value. There are valid objections to small plots. Suppose we have a small plot which consists of only five rows of whatever crop is under trial. If the edges of that plot border on an uncropped area such as a path, or on another plot which is given much better or worse agricultural treatment, the outside rows are bound to be affected by the competition for light and root space, and are likely to differ from the three inner rows. In this instance therefore two-fifths of the plot are affected by conditions other than those which are being consciously imposed by the treatment under trial. The larger the plot, the less this type of interference will occur. Every experimenter has to consider plot size in this light, but the objection usually raised is made even when the border effect is slight: agriculturists tend to think in terms of acres rather than in their fractions. There is however one over-riding consideration which puts a sharp limit to plot size. Any tract of land on which experiments are carried out will be heterogeneous in productive capacity. It is to counter this that the elaborations of technique have been introduced. But it is a definitely established fact that pieces of land are likely to be more similar to each other when they are close together. This is obviously common sense. From the point of view of an accurate *comparison* of effects, therefore, it is essential to make use of that similarity to full capacity, and that is done by using small plots. The real ground of the objection is that when translated into gross yields per acre, the data

from small plots will exaggerate figures for cropping capacity. This is to some extent true, but it is not such a grave objection as is sometimes made out, and for two reasons. Firstly, absolute yield responses are seldom of importance: it is the comparison that matters. On another farm, or estate, quite different absolute values would be obtained even if plots were large. It is advantageous therefore to forego the illusory advantage of seemingly rational absolute yields, in favour of the more solid advantage of accurate comparisons. Secondly, the absolute yield levels from a replicated experiment are not as illogical as they seem at first glance. Suppose we have 5 treatments replicated 10 times with a unit plot of a tenth of an acre. The total area will be 5 acres and the area devoted to any particular treatment will be an acre. The whole argument for random distribution and replication rests, as the foregoing considerations have striven to make plain, on achieving a *representative* sample. This being so, the 10 small plots are not merely representative of yields from an acre of land but of the whole 5 acres. It is not necessary to have the entire 50 plots all disposed in one compact block. They can be dotted about a much larger area in 10 groups, each containing a representative of the 5 different treatments. If this were done in a 50-acre field, then the sample would be reasonably representative of the whole 50 acres though each treatment occupied only one acre.

There are many other refinements which are introduced into field experiments all with the same aim, to make the comparisons accurate and the data representative, but these need not be considered here. The main objections

have been answered in all respects except cost. Here again, conditions vary greatly from place to place and from time to time. It is better to answer the agricultural question satisfactorily and then leave the economic aspects to be reviewed from time to time and from place to place. There is much to be said for following up accurate field experimentation with large-scale demonstrations of the most important effects on varying soils, as indicated by soil surveys, and under differing climates. This is the final stage. To try to sort out the best from the worst treatments in a large-scale experiment, as a first attempt, is a waste of time, land and money.

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